QUALITY OF SERVICE ESTIMATION TECHNIQUES FOR AN OPTICAL VIRTUAL PRIVATE NETWORK OVER WDM/DWDM NETWORK

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by

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under the guidance of

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Dedicated to

My inspiring Parents and Wife

Declaration

I certify that

a. the work contained in this thesis is original and has been done by me under the guidance of my supervisor.
b. the work has not been submitted to any other Institute for any degree or diploma.
c. I have followed the guidelines provided by the Institute in preparing the thesis.
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Certificate

This is to certify that the thesis entitled, **Quality of Service Estimation Techniques for an Optical Virtual Private Network over WDM/DWDM Network**, submitted by **Santos Kumar Das** to National Institute of Technology Rourkela, is a record of bonafide research work carried under my supervision and is worthy of consideration for the award of the degree of Doctor of Philosophy of the Institute.

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Date: 26^{th} December, 2014.

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"The will of God will never take you where grace of God will not protect you."
Thank you God for showing me the path...

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"We have to work, constantly work with all our power, to put our whole mind in the work, whatever it be, that we are doing. At the same time we must not be attached. That is to say, we must not be drawn away from the work by anything else; still, we must be able to quit the work whenever we like."

Santos Kumar Das

Abbreviations

AR	Adaptive Routing
ADM	Add-Drop Multiplexer
ASE	Amplifier Spontaneous Emission
BER	Bit Error Rate
CD	Chromatic Dispersion
CE	Customer Edge
CM	Control Manager
CQ	Connection Quality
DWDM	Dense Wavelength Division Multiplexing
ETED	End-To-End Delay
ETETD	End-To-End Total Delay
EMOBRWA	Existing Middle-Outer Band with Random Wavelength Assignment
FC	Filter Concatenation
FR	Fixed Routing
FAR	Fixed Alternate Routing
FWM	Four Wave Mixing
FFWA	First Fit Wavelength Assignment
GMPLS	Generalized Multi-Protocol Level Switching
HC	Hybrid Crosstalk
IB	In-Band
IP	Internet Protocol
INBFWM	In-Band and Four-Wave Mixing
L1VPN	Layer 1 Virtual Private Network
LC	Linear Crosstalk
LI	Linear Impairment
MOBRWA	Middle-Outer Band with Random Wavelength Assignment
NLI	Non-linear Impairments

OCR	Optical Core Router
O/E/O	Optical-to-Electrical-to-Optical
OADM	Optical Add-Drop Multiplexer
OB	Out-Band
OXC	Optical Cross Connect
OCS	Optical Circuit-Switched
OVPNCM	Optical Virtual Private Network Control Manager
OVPN	Optical Virtual Private Network
OVPNC	Optical Virtual Private Network Connection
OVPNCR	Optical Virtual Private Network Connection Request
OVPNCWA	OVPNC/Wavelength Assignment
PER	Provider Edge Router
PLI	Physical Layer Impairment
PMD	Polarization Mode Dispersion
PDL	Polarization Dependent Loss
PIOB	Proposed Inner-Outer Band
PIOBFFWA	Proposed Inner-Outer Band with First-Fit Wavelength Assignment
PIOBRWA	Proposed Inner-Outer Band with Random Wavelength Assignment
QoT	Quality of Transmission
QoS	Quality of Service
RWA	Routing and Wavelength Assignment
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering
TDR	Transmission Data Rate
VPN	Virtual Private Network
VC	Virtual Circuit
WDM	Wavelength Division Multiplexing
WFC	Wavelength with different Fiber Composition
WCC	Wavelength Continuity Constraint
WDC	Wavelength Distinct Constraint
WA	Wavelength Assignment
XPM	Cross-Phase Modulation

List of Important Symbols

$T(i,j)$	Connection matrix for link (i,j)
DS_{PMD}	Polarization mode dispersion coefficient in $ps/(km)^{1/2}$
$L(i,j)$	Length of a link (i,j) in km
TDR_c	Computed transmission data rate in $Tbit/s$
D_{WFC}	Delay due wavelength with different fiber composition (WFC) in ps
$W(i,j)$	Wavelength vector link (i,j)
N_λ	Total number of wavelengths per link
W_{N_λ}	Set of wavelengths
λ_l	l^{th} wavelength in nm
K_{fs}	Total number of fiber span
δ	Pulse broadening factor
(s,d)	Source-destination pair for a connection request
(m,n)	OVPN client pair
$SOVPNC$	A set of OVPNC
$OVPNC^k$	k^{th} OVPNC
$ETED_c$	Computed end-to-end delay in ps
QF_c	Computed Q-Factor
QF_h	Highest Q-Factor
RQF	Required Q-Factor
RDR	Required data rate in $Tbit/s$
RD	Required data rate in ps
D_{CD}	Delay due to chromatic dispersion in ps
DS_{CD}	Chromatic dispersion coefficient in $ps/nm-km$
D_{PMD}	Delay due to polarization mode dispersion in ps
D_{MD}	Delay due to modal dispersion in ps
D_{WGD}	Delay due to waveguide dispersion in ps
D_{TD}	Total delay in ps
$ETETD_c$	Computed end-to-end total delay in ps

n_1	Refractive index of core
n_2	Refractive index of cladding
c	Velocity of light in m/s
V	Frequency parameter in a fiber link in Hz
a	Diameter of the core in μm
Δ	Change in refractive index
$\nabla\lambda$	Spectral width of the light source in nm
BP	Blocking probability
$TNCB$	Total number of connection blocked
SD	Total number of source-destination pairs
NT	Total number of OVPN Type
NI	Total number of OVPNC group
NP	Total number of Possible OVPNC requests
$cgroup$	Array of Connection request groups
HH	Total number of OVPNC
$TNCA$	Total number of connection accepted
$LC(i, j)$	Cost of link (i, j)
Q_i	Q-Factor at i^{th} node
δ_{eye}	Eye penalty in dB
δ_{noise}	Noise penalty in dB
p^i	Signal power at i^{th} node in mW
F	Noise figure in dB
α	Attenuation constant in dB
δ_{pmd}	Polarization mode dispersion in $ps/(km)^{1/2}$
δ_{cd}	Chromatic dispersion in ps
pdf	Probability density function
E_{ds}	Desired optical signal
$E_{\varepsilon k}$	Interfering signal
ω	Nominal optical angular frequency
ϕ	Independent phase fluctuation of each optical source
P_{ds}	Signal power of the received/desired signal at the receiver in mW
ω_{ds}	Nominal optical angular frequency of the desired signal
ω_k	Nominal optical angular frequency of the interfering signal
ϕ_{ds}	Phase fluctuation of desired optical source
ϕ_k	Phase fluctuation of interfering optical source
b_{ds}	Binary symbol of the desired signal
b_k	Binary symbol of the the interfering signal

P_s	Signal power at source s in mW
ε_k	Crosstalk level (relative power) of the k^{th} interferer/crosstalk in dB
P_k	Optical power of the k^{th} interferer/crosstalk in mW
b	Binary symbols forming the amplitude modulated signal
$\vec{r}$	State of polarization of signal and interfering crosstalk
E_{ph}	Total incident optical field on the photo detector
i_{ph}	Field intensity/photo current received at photo detector in mA
ρ	Detector/receiver responsitivity
η_q	Quantum efficiency
q_e	Electron charge
PE_{ph}	Photon energy
ϑ_k	Random phase
$n_{ov}(t)$	Overall receiver noise
$n_g(t)$	Gaussian noise in the receiver
$p_{n,k}$	Probability density function for noise photo current
σ^2	Variance of receiver thermal noise
σ	Receiver thermal noise power
σ_0^2	Variance of the receiver thermal noise when "0" is transmitted in mA
σ_1^2	Variance of the receiver thermal noise when "1" is transmitted in mA
$erf(....)$	Error function
I_{th}	Detection threshold in mA
I_{ds}	Photo current of the desired signal in mA
$f(y)$	Weighting function for a random variable y
$erfc(....)$	Complimentary error function
SNR_{inb}	Signal-to-noise ratio for in-band crosstalk
p_{be}^{inb}	Bit-error probability due to in-band crosstalk
$\lambda_{p,q,r}$	FWM component generated for p^{th}, q^{th} and r^{th} wavelengths
M	Number of FWM component
$P_{pqr}(i,j)$	FWM power in an optical link (i,j) in mW
γ	Non-linear coefficient in $(w.km)^{-1}$
L_{eff}	Effective fiber length in km
A_{eff}	Effective area in cm^2
η	Efficiency of the FWM
β_{pqr}	Phase-matching factor

λ_k	Central wavelength in nm
D_c	Fiber chromatic dispersion in $ps/nm-km$
n_{ef}	Efficiency order
$\Delta\lambda$	Wavelength difference between two channels in nm
σ_{FWM}	Induced noise power in dB
P_{be}^{FWM}	Bit-error probability due to FWM
SNR_{FWM}	Signal-to-noise ratio for FWM crosstalk in dB
σ_{hc}	Noise power due to hybrid crosstalk in dB
p_{be}^{hc}	Bit-error probability due to hybrid crosstalk

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Abstract

Quality of Service (QoS) in optical virtual private network (OVPN) is a demanding factor for communication network application. To provide desired QoS, the control plane in an all optical network (AON) has to be designed to maximize the quality of an OVPN connections (OVPNC). The AON is generally characterized by various network and physical layer parameters, which are used by the OVPN control manager (OVPNCM) for the estimation of quality factor (Q-Factor) for a set of possible OVPNC. It is observed that, not only the network layer parameters, but also the physical layer parameters called as physical layer impairments (PLIs) have impact on connection quality. In optical networks, the PLIs are incurred by non-ideal optical transmission media and accumulate along the optical connection. The overall effect of PLIs can be analyzed to determine the feasibility of quality based OVPNC. It is important to understand the process and provide the network as well as the PLI information to the OVPNCM and use this information efficiently to compute feasible connections along with Q-Factor values. Based on these, four different QoS estimation techniques have been proposed here.

- In recent years, several fiber manufacturing companies are competing with each other to provide the better quality fiber. Though all companies claim their fiber is the best one, there exists no standard technique to prove the quality of a fiber. To overcome this, a technique for quality based fiber material selection is proposed. This technique can be adopted by the service provider network before the deployment in optical fiber network. The proposed technique estimates the Q-Factor of a connection (link) based on fiber dependent end-to-end delays (ETEDs) and dispersion dependent transmission data rates (TDRs). The estimated Q-Factor values are used for the selection of appropriate fiber material as well as for the selection of high quality OVPNCs to the OVPN clients.

- The ETEDs not only depend on wavelength but also on other parameters such as fiber dispersions that are prominent in high speed networks. In order to cope with those dispersion effects, the technique of Q-Factor computation is proposed. This technique is used for dynamic selection or assignment of a suitable OVPNC to the OVPN client as per the QoS requirements.

- The fiber dispersions not only incur delays in connections but also impact on noise and eye penalties. Based on these penalties, the estimation of OVPNC quality is proposed for the selection of quality based connection.

- Other than the impact of various dispersion effects on connection quality, it has also the impact of linear crosstalk such as in-band (IB) and nonlinear crosstalk such as four-wave mixing (FWM). Based on the mixing effect of IB and FWM crosstalk, a hybrid crosstalk (HC) model is proposed. This HC model along with a wavelength assignment technique is used for the selection of high quality OVPNC.

In short, this thesis work proposes four different QoS estimation techniques for OVPN to evaluate the connection quality.

Keywords: WDM, DWDM, Optical virtual private network, Lightpath, QoS, Q-Factor, Physical layer impairments, Transmission data rate, End-to-end total delay, Dispersion, Eye penalty, Noise penalty, In-band Crosstalk, Wavelength assignment, FWM.

Contents

CHAPTER 1

Introduction

Preface

An optical fiber provides transmission over a frequency range of about 25 terahertz with a very low transmission error rate of 10^{-9}, which is in orders of magnitude higher than available in copper cables or any other transmission medium. This property allows use of fiber cable over long distances at high data rate leading to widespread use of today. This chapter presents an Introduction to the concept of optical virtual private network (OPVN), outlines the Scope of the work, Motivation behind the work, Problem definition and Organization of the thesis.

1.1 Introduction

The traditional Internet Protocol (IP) supports only the best effort traffic, which cannot supply sufficient quality of service (QoS). Optical circuit-switched (OCS) networking technologies are better suited to support wide ranges of QoS needed in advanced scientific applications [1]. Recently, QoS based optimal co-scheduling of computing resources and network resources for OVPN connection (OVPNC) establishment over optical networks have drawn much attention among the researchers. Most of the proposed works [2–4] for establishing OVPNCs are based on static scheduling strategies. OVPN provides service to the customer in the form of optical connection. It is also expected to be one of the major applications in future optical networks. It can be a favorable approach for realizing the next generation virtual private network (VPN) services [5, 6] by providing a guaranteed QoS [7], which requires a good control (signaling) manager (CM) for all the optical routers available in the optical domain. CM can be either centralized or distributed, that deals with various physical layer impairment (PLI) [8] dependent QoS parameters such as transmission data-rate (TDR), end-to-end delay (ETED), noise penalty, eye penalty and bit-error rate etc. In centralized control, a request from the client is received at access node/router and goes to the CM, where the routing and wavelength assignment (RWA) algorithm is used to find a suitable connection for the request. When an access node no longer requires a connection, it informs the CM to release the connection. The advantage of this method is that the released connections can be utilized in an efficient way, as the CM maintains up-to-date network state information. When the network traffic load increases, the central manager requires sufficient buffer and processing power to handle all the requests. In distributed control approach [9–11] a network can be thought of as two-level (two-plane) network with a data network (data plane) and a shadow network (control plane) having the same topology as that of the physical network. The data plane contains several wavelengths and is used for transmitting data. The control plane is used to exchange control signals. A single wavelength on every link can be used as a control wavelength for exchanging control messages. The same can be applied in centralized control system, where the backbone network acts as a data plane and all the connected routers/nodes to the provider/control manager acts as a control plane.

1.2 Organization of the Chapter

The rest of the chapter is organized as follows. Motivation behind the research work is discussed in Section 1.3. Problem definition is mentioned in Section 1.4. The Scope of the thesis are summarized in Section 1.5. Finally, the Organization of the thesis is mentioned in Section 1.6.

1.3 Motivation behind the Research Work

Current research in networking have focused on building intelligent networks [12], which can be a wired or wireless. Todays transport networks are based on optical fiber. Therefore, it is desirable to built intelligent optical network. This network should consist of wavelength-division multiplexing (WDM)/dense wavelength-division multiplexing (DWDM) based optical components like optical-add-drop multiplexers (OADMs) and optical cross connects (OXCs). The networks should also have full knowledge of the wavelength status, traffic and physical layer impairments (PLIs). Moreover, the intelligent optical network should be self-controlled. With increase in the number of users and variety of applications, the demand for QoS have also increased. The next generation intelligent network should able to support various applications and the QoS as demanded by the users. Above factors motivated us to investigate on QoS based OVPN, which can make use of the concept of intelligent network. This mechanism computes the quality factor (Q-Factor) for a possible set of OVPNCs. Depending on the QoS requirement of the clients, the edge routers can assign or block the connections requests. The goal of this thesis is to design a framework to dynamically select an OVPN connection based on required or highest Q-Factor.

1.4 Problem Definition

Given a network topology $\mathcal{G} = (V, E)$, the goal is to analyze the quality of a possible set of connections and select an appropriate connection, $\mathcal{OVPNC}$ for a client using some anonymization function f_A: $\mathcal{G} \rightarrow \mathcal{OVPNC}$, subjected to the following conditions:

- Satisfy the required or highest quality of the client,
- Availability and assignment of appropriate wavelength,
- Minimal signal interference/crosstalk and
- Minimal blocking probability

Here, V denotes the set of nodes/routers and E denotes the set of point-to-point single-fiber links.

1.5 Scope of the Thesis

The objective of this research work is to develop the QoS estimation techniques for optical virtual private network over WDM/DWDM Network. The techniques are listed as under.

- Development of a centralized OVPN system model for the estimation of OVPNC quality in term of Q-Factor based on different fiber materials.
- Development of centralized OVPN system model for the estimation of OVPNC quality based on total dispersion effect in a connection.
- Development of QoS estimation technique based on linear impairments such as chromatic dispersion, polarization mode dispersion and amplifier spontaneous emission noise.
- Development of QoS estimation technique based on hybrid impairment constraints such as in-band and four-wave mixing crosstalk.

1.6 Organization of the Thesis

Following this introduction, the remaining part of the thesis is organized into following chapters:
Chapter 2: This chapter describes the overview of QoS in OVPN and related discussions.
Chapter 3: This chapter describes a centralized QoS framework model for an OVPN system. The proposed model estimates the wavelength dependent ETED with different fiber materials composition and dispersion based TDR of a connection. QoS is computed by using ETED and TDR values and expressed in terms of Q-Factor for a list of possible OVPNCs of a source-destination pair. The estimation of Q-Factor can provide insight about the consideration of appropriate fiber material type for the selection of high quality OVPNC in order to provide better quality to the OVPN clients.
Chapter 4: This chapter deals with the effect of various dispersions and fiber composition based parameters for the computation of Q-Factor of an OVPNC, which are prominent in high speed networks. A QoS estimation technique is proposed for the dynamic selection of a suitable OVPNC as per the QoS requirements from the frequent arrival of OVPNC requests.
Chapter 5: This chapter deals with eye and noise penalty based on linear impairment

constraints such as chromatic dispersion, polarization mode dispersion and amplifier spontaneous emission noise. These parameters are expressed in terms of Q-Factor. The estimated Q-Factor is used efficiently in control plane for the selection of OVPNC.

Chapter 6: This chapter analyses the impact of linear and nonlinear crosstalk such as in-band and four-wave mixing on transmission performance of a transparent WDM/DWDM network. The traditional RWA algorithms have little impacts during the computation of connection quality . Hence, it cannot guarantee the OVPNC quality. In order to achieve guaranteed quality, a hybrid crosstalk aware RWA algorithm is proposed for the selection of high quality OVPNC.

Chapter 7: Finally, chapter 7 presents conclusions, limitations and discusses recommendations for application and further research on QoS estimation techniques which are discussed in the thesis.

CHAPTER 2

QoS in Optical Virtual Private Network - An Overview

Preface

This chapter presents the literature survey along with the related discussions on the concept of QoS based VPN over WDM /DWDM, which is also known as OVPN.

2.1 Introduction

Optical network is a communication network in which information is transmitted as optical signals. It has several advantages over electrical signals, including shorter data transmission delay time. The most important is the greatly increased bandwidth provided by the photon signals. In addition, a single strand of fiber used in optical network can carry optical signals at different wavelengths and that's why, it is also known as WDM/DWDM network. This type of networks have been making "waves" recently, following the opening of the national long distance market.

2.2 Organization of the Chapter

The rest of the chapter is organized as follows. The theoretical background of Optical network technology related to our research work is explained in Section 2.3. Section 2.4 gives Related works.

2.3 Optical Network Technology

This section explains the theoretical background of optical network technology related to the thesis work such as WDM/DWDM network, OVPN, QoS constraints in OVPN, RWA and OVPN system architecture.

2.3.1 WDM/DWDM Network

In an all-optical WDM/DWDM network, no optical-to-electrical-to-optical (O/E/O) conversion of data takes place at the intermediate routers, thus reducing the burden on the underlying electronics. Optical networks are capable of providing more functions than just a point-to-point communication (IP based network). Typically the bandwidth that an optical network can support is in the order of Tera bits per second (Tbit/s). However, the electronics network available today can not process this high data rate offered by optical network. Modern systems can handle up to 160 wavelength channels and can thus expand a basic 10 Gbit/s system over a single fiber pair to over 1.6 Tbit/s. In first generation networks, the electronics at a router not only handled the data intended for it but also controlled the traffic. This increases the burden on the underlying electronics substantially. To fully utilize the available bandwidth of an optical network faster electronic switching operating at Tera bit range is required. However, electronic circuits have their own limitation and current technology permits maximum speed in the order of Giga bits range.

WDM/DWDM networks have the potential to utilize the enormous bandwidth of optical fiber and at reduced opto-electronic miss-match. WDM/DWDM networks are the second generation optical networks, where data are routed through nodes (routers) in the optical domain. It is of two types such as opaque and all optical network (transparent). Opaque network is used in early stages, which consumes more power. Another problem with these networks is that, they are not scalable to satisfy future demands. These drawbacks can be overcome by transparent networks, which are scalable with higher data carrying capacity and consume less power. This is achieved since, all-optical WDM/DWDM network eliminates [13, 14] the conversions between electricity and light.

DWDM is the most innovative and advanced technology in fiber optic communication system due to its potential ability to provide huge bandwidth over a single fiber channel [15]. DWDM technology uses more closely spaced wavelengths. Therefore, a large number of wavelengths can be multiplexed and leading to optical fiber with higher capacity. One of the important features of DWDM technology is that, it can amplify the entire wavelength simultaneously without the need of O-E-O conversion and it can carry signal of different light speed and transmits data simultaneously through the optical fiber.

2.3.2 Optical Virtual Private Network

VPN is a virtual circuit (VC) and can be defined as an end to end connection with a set of quality of transmission parameters associated with it [16]. VPN services are very important in current networks. It is a virtual network since it is not built physically and separately, but it is only a split and allocated part of resources of a public network of a provider. It is private since it serves a closed group of users. It performs RWA function of taking a data from its source and delivering to its destination. The IP based VPN can realize only point-to-point connection oriented services [17, 18]. To provide advanced services, the IP based network service provider may need: i) flexible control and management service, and ii) Multiple customers/networks accommodation. In order to realize the above mentioned features, several proposals are mentioned in [19, 20]. Characteristics of OVPN can be summarized as: i) connectivity is restricted within a set of customers, where connectivity means data plane connectivity as well as control and management plane connectivity and control, ii) management information for one OVPN is never informed to the rest of OVPNs, and ii) some level of control and management functionalities is given to customers, where customers can reconfigure network topology, as well as reflect their own operational policy over the provider's optical network virtually dedicated to each OVPN. These functionalities changes depending on service requirements from customer. VPN can be classified as customer edge (CE) based, network based, customers provisioned, provider provisioned, connection oriented, connectionless oriented, layer 1 VPN, layer 2 VPN and layer 3 VPN [5,20]. The requirement of OVPN can be classified based on: i) management plane such as specification of policy and network component information, and ii) control plane such as lightpath setup, connection request and topology information etc.

2.3.3 Quality-of-Service Constraints in OVPN

Network layer assumes that the physical layer is ideal, i.e., it does not have any impairment while making the routing decision. However, in reality the physical layer has a lot of impairment constraints and due to which, it significantly affects the signal quality during transmission. In order to guarantee a quality-of-transmission (QoT)/QoS, cross layer optimization methods are essential, where the network layer takes the impairment constraints from physical layer into their consideration. In [21], a cross layer model is proposed, where the physical layer model analyses the impairment's effect and keeps track of them. The QoT/QoS is measured analytically at the physical layer module and this information is provided as a feedback to the network layer module. Network layer after obtaining the information from physical layer module takes a suitable decision for the selection of the lightpath with a guaranteed signal quality. This work considers a lightpath as OVPNC.

PLIs encountered in WDM/DWDM networks can be classified into two categories: Linear Impairments (LIs) and Non-Linear Impairments (NLIs) [8,16,22]. LIs are generally static in nature and NLIs are dynamic in nature. LIs are independent of signal power and affect each connection individually, whereas NLIs depend on signal power and it is not only affect the individual connection but also cause due to disturbance in between the connections. Therefore, in an all-optical network, allocation of new connection affect the existing one. Figure 2.1 shows the brief classification of impairments in WDM/DWDM networks. LIs are caused due to chromatic dispersion, group velocity dispersion, effect of higher order dispersion, polarization mode dispersion and adjacent channel crosstalk. These impairments can be summarized as follows.

Chromatic Dispersion (CD): It is a term used to describe the spreading of a light pulse, as it travels down a fiber. CD is the phenomenon in which different spectral components of a pulse travel at different velocities resulting of optical pulse broadening and causes inter symbol interferences. When the signal travels though several fiber links, the total dispersion is the sum of the dispersion caused by the individual links. In high speed networks, it causes a serious limitation in achievable data rate.

Polarization Mode Dispersion (PMD): Fiber deployed in a network may contain im-

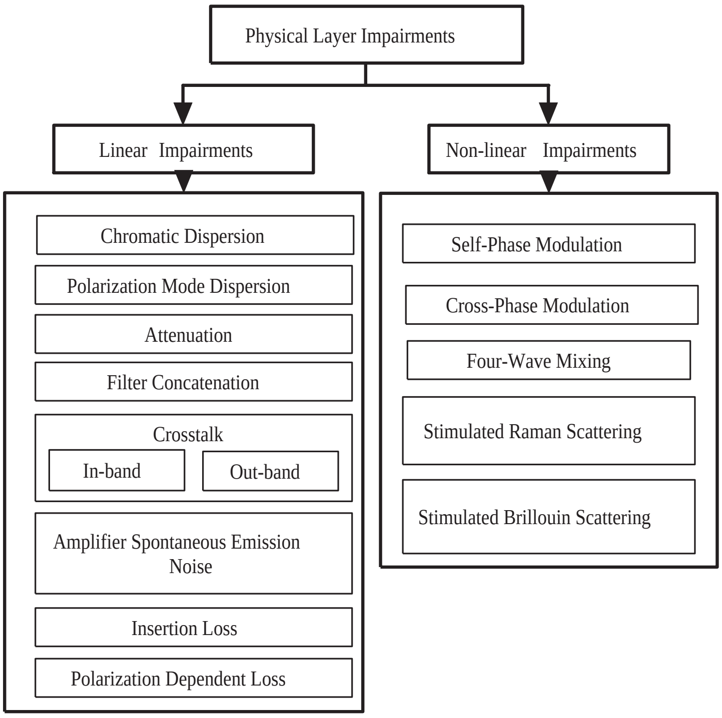


Figure 2.1: Classification of impairments in WDM/DWDM network.

purities during manufacturing process or may be subjected to environmental stress such as local movement and heating. These impurities and irregularities result in different polarization of the optical signal that causes different group velocities, so that pulse spreads in the frequency domain. This is known as PMD.

Amplifier Spontaneous Emission (ASE) Noise: ASE noise is produced by the optical amplifiers used at the intermediate routers, repeaters and preamplifier before the receiver. It is quantified in terms of noise figure, which represents how much higher the noise power spectral density of the amplified output as compared to input noise power spectral density and is often specified in decibels (dB). Amplifiers emit noise in both forward and backward direction, but only the forward noise will co-propagate with the signal to the receiver where it degrades the system performance. Counter propagating noise limits the achievable gain of the amplifier and increases the noise level. Its effect can be reduced by increasing the input laser intensity, tuning the master oscillator so that it is resonant with the amplifier, or by decreasing the amplifier facet reflectivity.

Polarization Dependent Loss (PDL): The two polarization components along the two axes of a circular fiber suffer different rates of loss due to irregularities in the fiber, there by degrading signal quality in an uncontrolled and unpredictable manner and it introduces fluctuations in optical signal-to-noise ratio (SNR). It is a measure of peak-to-peak difference in transmission of an optical system with respect to all possible states of polarization and is represented as $PDL_{dB} = 10log(\frac{P_{max}}{P_{min}})$, where P_{max} and P_{min} are the maximum and minimum output power. It mainly occurs in passive optical components. It is measured by polarization scanning techniques or Mueller matrix method [8].

Linear Crosstalk (LC): LC arises due to incomplete isolation of WDM/DWDM connection by optical components such as OADMs, OXCs, multiplexer/de-multiplexer and optical switches. In other words, it occurs due to leakage of power from other WDM connections on the desired connection. LC can be either out-band (OB) or in-band (IB) [23]. IB crosstalk has adverse effect in comparison to OB crosstalk as it lies in the same nominal wavelength as the desired signal. Figure 2.2 shows the representation of a signal with in-band crosstalk in optical networks. In ideal case, there is no crosstalk as two signals are

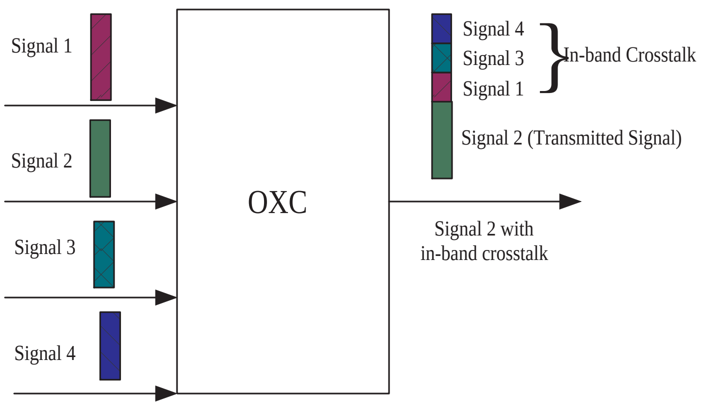


Figure 2.2: Signal with in-band crosstalk

routed to different output ports. However, any leaking or in-sufficient isolation induces homodyne crosstalk.

Filter Concatenation (FC): The narrowing of spectral width of the signal, as it traverses through a set of filters along a connection is called FC effect. The penalty induced by FC depends on the route, the modulation type, and the number of network elements through which the signal traverses before it reaches the destination.

In case of WDM systems, the nonlinear effects depend on the refractive index due to the intensity of the applied electric field. It is proportional to the square of the field amplitude. At sufficiently high optical intensities, non-linear refraction occurs in the core. It is the variation of refractive index with light intensity. This makes NLIs in optical networks since long-haul transmission commonly relies on high power lasers to transmit optical pulses over long spans to overcome attenuation. The important NLIs can be summarized as follows.

Self-Phase Modulation (SPM): SPM arises due to variation of refractive index of the fiber with intensity of the signal. An induced phase-shift occurs due to these variations and thus, different part of the pulse undergoes different phase shift resulting in chirping of the pulses. Chirping enhances the pulse broadening effect (in frequency domain) leading to CD. These effects are more profound in systems transmitting high power (especially in long-haul communication). In systems operating above 10Gbps or having lower data-rate but higher transmitting power, SPM significantly increases the pulse broadening effect of chromatic dispersion.

Cross-Phase Modulation (XPM): The variation of refractive index of the fiber not only depends on the intensity of the pulse but also on the intensity of the other co-propagating optical pulses. The fluctuation in the intensity of other pulses causes phase modulation of the pulse and it is termed as XPM. It results asymmetric spectral broadening and distortion of the pulse shape. It has more adverse effect than SPM and influences severely when the numbers of connections (wavelengths) in the fiber are high. The XPM induced phase shift occurs when two pulses overlap in time. Due to this overlapping, the chirping gets enhanced leading to pulse broadening. Its effect can be reduced by increasing the wavelength spacing between the channels or judiciously selecting the bit rate of adjacent channels that are not equal to the present channels.

Four-Wave Mixing (FWM): When WDM/DWDM system operates at frequencies $f_1, f_2, ..f_n$, the variation of refractive index not only induces phase shift within the channel but also gives rise to signals at new frequencies such as $2f_i - f_j$ and $f_i + f_j - f_k$. In comparison to SPM and XPM, FWM effect is independent of the bit rate of the system but is critically dependent on the wavelength spacing and CD of the fiber. FWM effect increases as the channel spacing decreases. Its effect has to be considered even when the data-rate is moderate and when dispersion shifted fiber is used. In general for W number of wavelength launched into a fiber, the number of four wave channel produced is $W^2(W-1)/2$.

Stimulated Raman Scattering (SRS): When two or more optical signals at different wavelengths are injected into a fiber, the SRS causes optical power from lower wavelength channels to be transferred to the higher wavelength channels. This can skew the optical power distribution among the WDM/DWDM connections reducing the SNR of the lower wavelength connections and introducing crosstalk on higher wavelength connections. Both of these effects significantly reduce the data carrying capacity of the fiber. It occurs at higher optical power than stimulated brillouin scattering. It scatters in both forward and backward direction. SRS effect can be reduced by using optical filtering techniques.

Stimulated Brillouin Scattering (SBS): SBS is the most dominant fiber non-linear scattering effect. SBS occurs when an optical signal in the fiber interact with the acoustic phonon. This interaction occurs over a very narrow line width. The scattering process is stimulated by photons with a wavelength higher than the wavelength of the incident signal. It sets an upper limit on the amount of optical power that can be launched into an optical fiber. When input power exceeds the threshold value, a significant amount of transmitted light is redirected back to the transmitter leading to saturation of optical power in the receiver, and introduces noise that degrades the system performance.

2.3.4 Routing and Wavelength Assignment

RWA refers to the process of establishing connection between a source-destination pair and assigning wavelength [24, 25] to it. Now-a-days in WDM/DWDM network, a single fiber can accommodate upto 120 wavelengths and expected to increase in future [26]. The objective of RWA algorithm is to achieve the best possible performance within the limits of the physical constraints. It is known to be NP-complete, therefore it is usually addressed by a two-step approach: First, finding a connection for a source-destination pair using a routing technique, and second, selecting of a free wavelength on the chosen connection using a wavelength assignment (WA) algorithm.

Routing Technique

In this section some of the important routing/lightpath selection techniques are discussed.

Fixed Routing (FR): Fixed routing is a technique in which a single lightpath for the given source-destination pair is computed [27]. FR technique is a very simple mechanism and due to less number of available lightpaths in the network, the blocking probability of connection request can be high.

Fixed Alternate Routing (FAR): Several alternate connections are calculated offline for a given source-destination pair in FAR [28, 29]. These connections are arranged in some priority basis. Usually the shortest connection is the most prioritized one. In certain cases, the number of links in the connection can also be a criteria for prioritizing. When connection request arrives, the source node searches for a connection to destination until it finds a connection with a free wavelength for connection establishment. If connection is not available, then a connection request will be blocked. This technique of routing provides alternate connection for a connection request hence link failure problem can be solved. The blocking probability can be reduced in FAR method as compared to FR.

Adaptive Routing (AR): In AR technique, connections are computed online depending on network state and availability of resources [30]. Here, a connection for a source-destination pair is adapted dynamically depending on the network state and considering the shortest connection. When a connection request arrives, the shortest connection for a source-destination pair is computed. If more than one connections with same distance are present, the route is randomly selected and the request will be blocked if connection is not available. This is the most efficient routing technique for WDM/DWDM network. In this thesis, we followed the idea of AR technique.

WA Algorithm

The task of WA algorithm is to assign wavelength to each link on the selected connection. The RWA problem is subjected to various constraints such as wavelength continuity, wavelength distinct, physical layer impairment and traffic engineering.

Wavelength Continuity Constraint (WCC): In this scheme, all links on a connection is assigned with the same wavelength. The WCC distinguishes the wavelength continuous network from a circuit switched network which blocks calls only when there is no capacity along any of the links in the connection assigned to any connection request. This type of network suffers more blocking as compared to the circuit switched network. This degraded performance can be overcome by wavelength conversion techniques [31].

Wavelength Distinct Constraint (WDC): In this scheme, the links on the connection may be assigned with different wavelengths. Here, signal arriving at one wavelength is converted to another wavelength at an intermediate optical router and then forwarding the signal through another link. This technique is almost used in all WDM/DWDM network and is known as wavelength conversion method for WA. In wavelength convertible network, optical routers are capable of wavelength conversion and work similar to a circuit switched network, which blocks the connection request only if there is no available links carrying the capacity to forward the data [28]. In WDC, the effective resources i.e. the total effective connection for routing is more, hence the probability of blocking for incoming connection request is lower.

Physical Layer Impairment Constraint (PLIC): This constraint concerns how to select a wavelength and/or connection that guarantees the required level of signal quality.

Traffic engineering constraints (TECs): This aims to improve resource-usage efficiency and reduce connection blocking probability.

A few of the existing WA algorithms are explained below. These algorithms use either WCC, WDC, PLIC or TEC depending on the type of network architecture.

Random WA: In this scheme, a wavelength is selected randomly from a set of available wavelengths in a WDM/DWDM link. Generally a random number generator is used and wavelengths are assigned to the numbers.

First-Fit WA (FFWA): In FFWA method, a wavelength matrix is designed by arranging all wavelengths in ascending order. Then the wavelengths are numbered and the least numbered wavelengths are assigned for the first lightpath connection. Higher priority is assigned to the lower numbered wavelengths. Computation cost of this scheme is lower since it is not required to search for all wavelengths. The performance in terms of blocking probability, fairness and computation complexity is generally low [32]. In a wavelength-routed network, the traffic may be static or dynamic. In a static pattern, a set of connection requests are provisioned at a time and it remains for certain period of time, where the respective lightpaths are established simultaneously. In dynamic pattern, each lightpath is established as the connection request arrives and is released after certain period of time. This method considers the current traffic state of the network and lightpath provisioning is done accordingly. As the communication system grows, the bandwidth demand also increases leading to shortage of resources. For satisfying this, dynamic lightpath provisioning or on-demand lightpath established is preferred over static methods.

A general approach in form of flow chart for PLIs aware based RWA algorithm [8] is shown in Figure 2.3. In general, the RWA block is responsible for lightpath set up and

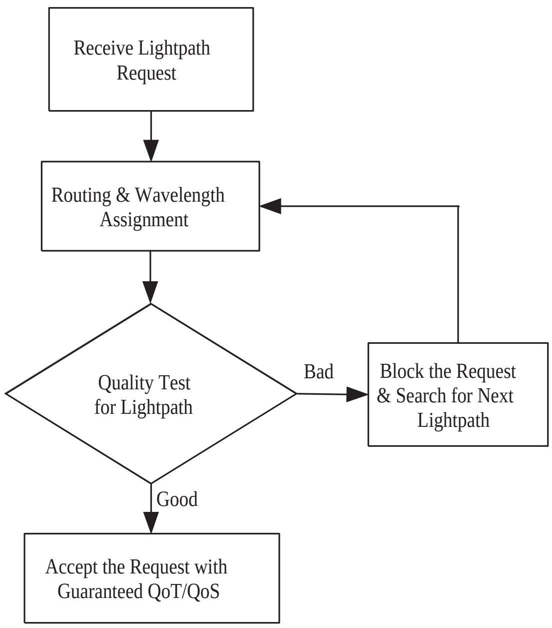


Figure 2.3: A general flowchart for PLIs aware RWA algorithms

RWA function is done either in two stages or in a single stage (integrated). In the quality test block, the QoT is considered by taking different PLIs into consideration. These PLIs may be obtained either by using the analytical model or by the manipulation of some real-time quality matrices (e.g. OSNR, BER and etc.). If the estimated OSNR or BER of a lightpath satisfies the threshold requirement of a call, then the connection is established, otherwise RWA algorithm may select an alternate lightpath and repeat the same procedure. If the alternate one doesn't satisfies the quality requirement, the call is blocked.

2.3.5 OVPN System Architecture

There exist two architectural models for OVPN system: centralized and distributed control. Centralized control architecture adopts a technique similar to circuit-switched telephone network, whereas, the distributed control architecture resembles the packet data networks such as the Internet. In the centralized architecture, a central manager monitors the network state as well as controls all resource allocations. When a connection request is received, an edge router sends a message to the central manager, which executes the RWA algorithm. Once a connection and a free wavelength are selected, the central manager reserves the resources on all the routers along that connection. However, the distributed control architecture broadcasts periodically about the network state, which enables each edge router to compute the connection upon receipt of a connection request. On receiving a connection request, an edge router first executes the routing algorithm to compute a connection and then it starts the wavelength-reservation protocol. The WA algorithm can be executed either by the destination router or by the source router to pick a free wavelength. In this thesis, we have followed a centralized based OVPN architecture [33].

2.4 Related Works

This thesis discusses QoS estimation techniques for OVPN over WDM/DWDM network. Related to QoS estimation techniques, this section overviews the background work done by several researchers.

The related distributed protocols for WDM network have been discussed in [9, 10, 34]. In [35], differentiated services architecture with aggregated flows based on the notion of per hop behaviors is discussed. In this scheme static decision is taken for the re-routing of specific flow. QoS based VPN over WDM network is discussed in [36], which attempts to support guaranteed QoS depending on the number of applications. In these reported works, the implication of end-to-end QoS support based on PLI constraints in IP-WDM domain have not been considered.

In [37], a multicast optical level switched path (OLSP) establishment mechanism for supporting high bandwidth multicast services in OVPN is discussed. It also suggests that, OVPN control mechanism is adaptive to the operation of routing and signaling protocols of generalized multi-protocol level switching (GMPLS). Resource reservation protocol (RSVP) [38] is a flow based protocol that support the individual flow requirements. This protocol is helpful to be considered as a reference point for OVPNC management. In [39], clients are supported with guaranteed QoS by a centralized Bandwidth broker. This architecture does not maintain any QoS reservation states at core router. It helps to relieve control mechanism at core routers and thus enables a network service provider to provide guaranteed services without necessarily requiring software/hardware upgrades at core routers. This implies the principle of centralized system. The effect of QoS during WA based on various PLI constraints is shown in [40]. In this paper, two of the path establishment algorithms such as shortest-path and the shortest widest path are deployed. The work in [41] proposed a framework to support OVPN. In this work, system performance is analysed at different number of wavelengths per link and different number of VPNs in one lightpath. Y. Qin et al. [42] explores the motivation and a framework for supporting on-line VPN service for different traffic type with different QoS requirements over optical WDM networks. This proposed work is more suitable for multimedia applications which have various sensitivity of delay and jitter. A FWM aware priority-based RWA algorithm for transparent optical networks is discussed in [43] for online discovery of a requested lightpath/connection. This work also considers the effect of ASE noise on a lightpath during transmission of optical signal from any source to the intended destination. In [44], RWA scheme is discussed for multiple constraints based optical networks. This paper proposes a distributed discovery wavelength path selection algorithm in order to reduce the path convergence time and blocking probability. The mitigation of transmission impairments, issues and challenges with RWA in optical WDM networks are discussed in [45]. This work reviews the impairments present in optical fiber emphasizing those that result in performance degradation of WDM system. The effect of PMD on QoS over optical test bed is discussed in [8,21,46,47]. The combined NLI effects on QoS are discussed in [48,49].

The above research works are mostly based on optical link level QoS analysis. The analysis of quality in optical connection level has not been mentioned by any of the works for the application of OVPN. Various PLI constraints should be analyzed together due to their high impacts on connection quality. The implication of end-to-end QoS support based on Q-Factor has not been considered in any of the reported works. Hardly any of the above work concentrates on network as well as the physical characteristics based Q-Factor computation for the selection of OVPN connection (OVPNC) as per the requirement of the client. In this research work, we are characterizing each OVPNC in terms of Q-Factor, which is a combination of multiple QoS parameters. The proposed work is focused on control plane to support end-to-end guaranteed QoS service to the OVPN clients.

2.5 Conclusion

This chapter presented an overview of the literature covering the optical network technology and related works on QoS estimation techniques.

CHAPTER 3

Fiber Material Based Estimation of OVPN Connection Quality

Preface

It is known that the network and physical layer parameters have the significant impacts on data transmission. These parameters decide the quality of an OVPNC. In this chapter, we propose a centralized OVPN system model for the estimation of connection quality in terms of Q-Factor. It is based on wavelength dependent ETEDs with different fiber material composition and dispersion dependent TDRs. Q-Factor of a connection is used for the consideration of appropriate fiber material in order to provide a better quality OVPNC to the OVPN client by the service provider network (SPN). It can be decided before the deployment of optical network. Q-Factor is a key parameter for selection of high quality OVPNC of a given source-destination client pair connected to the SPN. This chapter also analyses the blocking probabilities of various ranges of OVPNC requests (loads) by considering different fiber materials in the backbone network.

3.1 Introduction

In order to provide guaranteed QoS to the OVPN clients, an OVPN control manager (OVPNCM) can take various QoS parameters such as TDR and ETED into account while setting optical path. These QoS parameters can be computed from the physical layer constraints such as dispersion, fiber material composition and length of fiber link as well as from the network layer constraints such as wavelength and connectivity, etc. These parameters are considered in expressing the Q-Factor, which decides the quality of an OVPNC.

In WDM/DWDM network, the fiber material type may affects the quality of optical connection. This process is analyzed in this chapter. We proposed a model for OVPNCM based on the concept of differentiated services [35] used in IP network and GMPLS capable hybrid/opaque network [50]. It is a combination of IP and WDM network. However, the proposed model is considered only for transparent/all-optical-network (AON), where there is no need of electrical to optical signal conversion. A high quality OVPNC selection mechanism is proposed based on OVPN traffic and availability of resources at provider edge router and control information at OVPNCM.

The delay in fiber optics communication for OVPN can be neglected due to high speed data transmission. However, it can be used for the selection of fiber materials as well as for the computation of accurate connection quality. It matters when there is a need of guaranteed quality to the end customer. Hence, we have considered delay for the analysis of fiber characteristic in order to opt a better fiber, which can be used for network deployment at customer site. This also can help, to provide accurate OVPNC quality in order achieve guaranteed QoS.

3.1.1 Organization of the Chapter

The rest of the chapter is organized as follows. Section 3.2 gives a brief discussion on OVPN system model. Computation of Q-Factor is explained in Section 3.3. The Functional description of OVPN control manager is discussed in Section 3.4. The Simulation results and discussion are described in Section 3.5. Finally, the work is concluded in Section 3.6.

3.2 OVPN System Model

A generic OVPN system model [51] is presented in Figure 3.1. This model employs

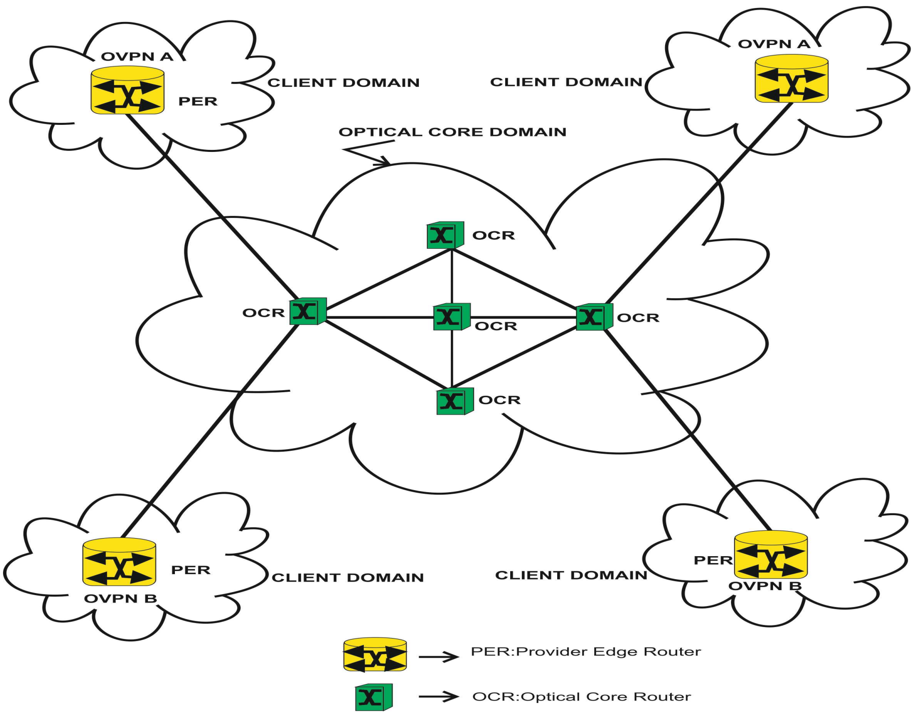


Figure 3.1: OVPN System Model

the concept of VPN over WDM/DWDM network. The wide area network connectivity is provided by the backbone optical core domain, which consists of several switch nodes interconnected by multi-wavelength links. The optical access routers (nodes) provide the optical interface to the OVPN clients. This system model comprises of multiple client domains connected over single optical core domain. The goal is to establish several OVPNCs on the physical network topology, where each OVPNC is specified by a set of routers.

3.2.1 OVPN Layering Structure

OVPN layers as shown in Figure 3.2 consists of three layers: the provider layer, OVPN client layer and the optical core layer [5]. These layers are controlled by the OVPNCM. As shown in OVPN system model, provider edge router (PER) belongs to an OVPN client domain, which provides OVPN services and interface to the attached clients and optical core routers (OCRs). OVPNC is established by setting up a tunnel between a source and destination clients.

Tunnel can be established either at layer 1, layer 2 or layer 3 of OSI model. In the provider layer, the PER is responsible for the non-local management functions such as management of optical resources, configuration and wavelength management, addressing, routing, topology discovery, traffic engineering, path restoration and etc. The provider

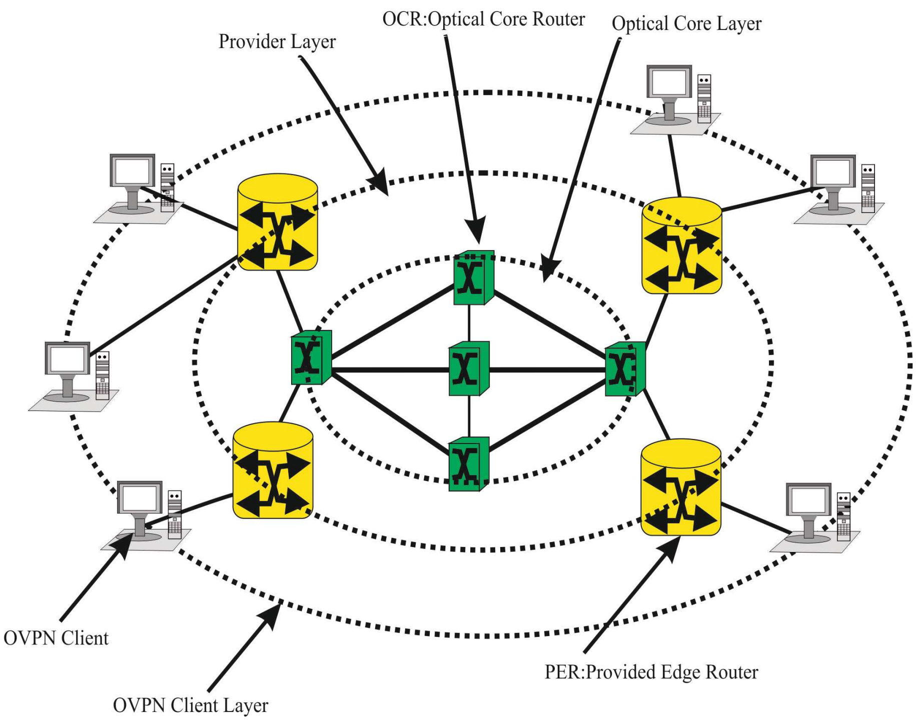


Figure 3.2: OVPN Layering Model

layer controls all the connection requests coming from OVPN clients. It is assumed that the SPN has access to optical components in the core optical network. Thus, it is reasonable to assume that the SPN has information about all optical equipments within its domain of control. All the routers presented in Figure 3.1 are controlled by the SPN, which is also known as the control plane.

3.2.2 Physical Topology

Physical topology of an OVPN is shown in Figure 3.3. It comprises of OVPN clients, connection requests, PERs, OCRs, an OVPNCM, and a central database etc. It is a centralized system model, that has data plane as well as control plane. Data plane deals with data transmission, where as control plane deals with management of network resources. The topology provides informations such as i) network connectivity, ii) availability of wavelengths, and iii) OVPNC requests. We have assumed multiple OVPNC requests originating from the OVPN clients.

OVPNCM maintains a traffic matrix (TM) for all OVPN clients. It also maintains the network resources as well as physical layer constraints such as routing information, TDR, ETED, and Q-Factor matrices for all possible OVPNCs of any source-destination OVPN client pairs. OVPNCM directly communicate with optical core routers and updates its

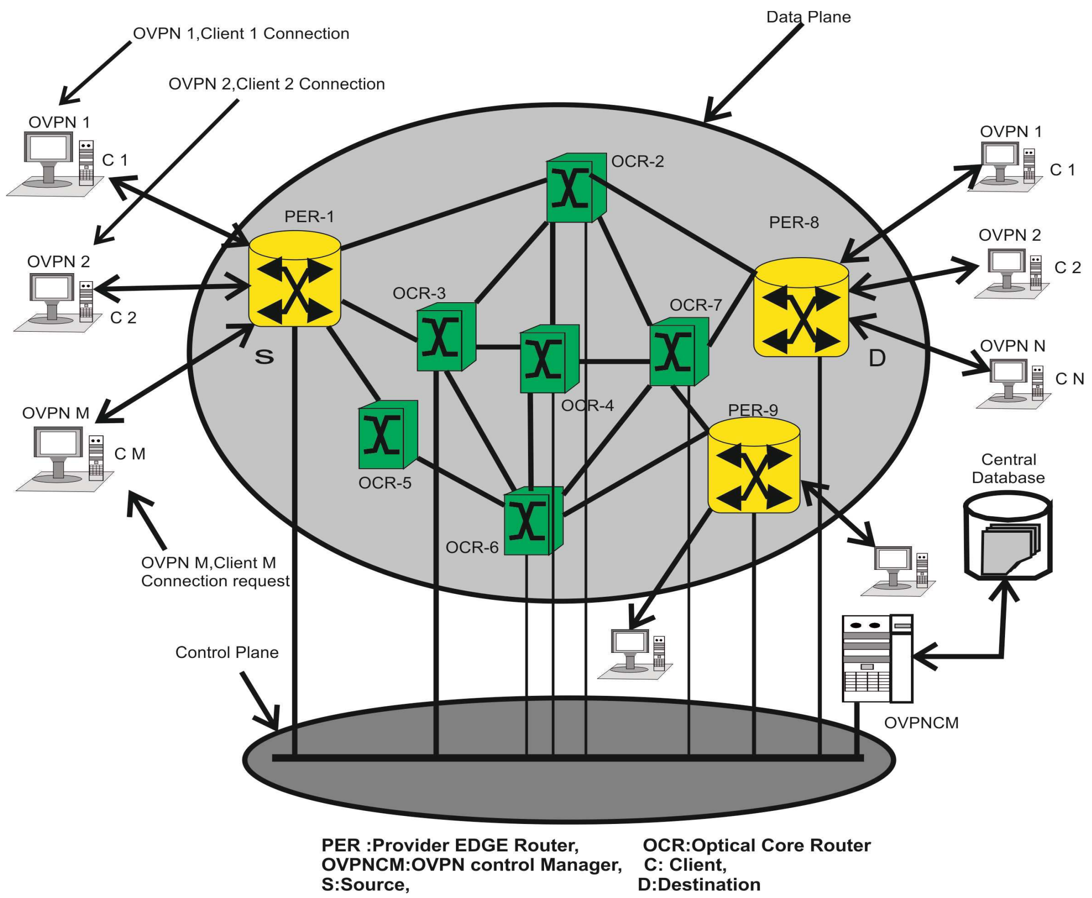


Figure 3.3: Physical Topology

information.

The connection matrix, $T(i,j)$ between any router pair i and j of the physical topology can be represented as

$$T(i,j) = \begin{cases} 1 & \text{if there exist a link between } (i,j); \\ 0 & \text{otherwise.} \end{cases} \tag{3.1}$$

The wavelength vector, $W(i,j)$ for a link (i,j) can be represented as

$$W(i,j) = \begin{cases} W_{N_\lambda} & \text{if } T(i,j) = 1; \\ 0 & \text{Otherwise.} \end{cases} \tag{3.2}$$

where, $W_{N_\lambda} = \{\lambda_1, \lambda_2, \ldots, \lambda_{N_\lambda}\}$ is a set of wavelengths; and N_λ is the total number of wavelengths available per link.

3.3 Computation of Q-Factor

Q-Factor is a computed quality value, that represents the quality of a connection. It is derived based on ETED and TDR, which are derived as under:

Transmission data-rate: Assuming a network link $L(i, j)$ consisting of K_{fs} number of fiber spans, where k^{th} span has length $L(k)$ with fiber PMD parameter $DS_{PMD}(k)$, where, $k = 1, 2, \ldots, K_{fs}$. The TDR of a link (i, j) strongly depends on the PMD [52]. This can be expressed as

$$TDR(i, j) \leq \frac{\delta}{\sqrt{\sum_{k=1}^{K_{fs}}(DS_{PMD}^2(k) \times L(k))}} \tag{3.3}$$

where the length of the link (i, j) can be represented as

$$L(i, j) = \sum_{k=1}^{K_{fs}} L(k) \tag{3.4}$$

Assuming all the fiber spans have the same PMD i.e.,

$$DS_{PMD}(1) = DS_{PMD}(2) = \ldots = DS_{PMD}(k) = \ldots = DS_{PMD}(K_{fs}) = DS_{PMD} \tag{3.5}$$

(3.3) can be written as

$$TDR(i, j) \leq \frac{\delta}{\sqrt{\sum_{k=1}^{K_{fs}}(DS_{PMD}^2 \times L(k))}} \tag{3.6}$$

$$TDR(i, j) \leq \frac{\delta}{DS_{PMD} \times \sqrt{\sum_{k=1}^{K_{fs}}(L(k))}} \tag{3.7}$$

The upper bound data-rate for the link (i, j) can be derived from (3.7) as

$$TDR(i, j) = \frac{\delta}{DS_{PMD} \times \sqrt{L(i, j)}} \tag{3.8}$$

where, the value of δ should typically be less than 10% of a bit's time slot for which the PMD can be tolerated and $DS_{PMD}(i, j) = L(i, j) = \infty$, when there is no link between i^{th} and j^{th} router pair.

Let us assume a set of connection, $SOVPNC(m, n, s, d)$ for (m, n) OVPN clients with a source-destination pair (s,d), that can be expressed as

$$SOVPNC(m,n,s,d) = \left\{OVPNC^1, OVPNC^2, \ldots, OVPNC^K\right\} \tag{3.9}$$

where, K is the number of possible OVPNCs for (m,n,s,d).
Assuming a k^{th} connection, $OVPNC^k(m,n,s,d)$ is defined as a group of links for (m,n) client with source-destination pair, (s,d). The overall computed transmitted data-rate, $TDR_c(m,n,s,d)$, for a k^{th} OVPNC can be derived from a single link to a group of links in a OVPNC. It is the minimum TDR among all the links of a k^{th} OVPNC, which can be represented mathematically as

$$\begin{aligned} &TDR_c(OVPNC^k(m,n,s,d)) = Min\{TDR(i,j)\}, \\ &\forall (i,j) \in OVPNC^k(m,n,s,d) \end{aligned} \tag{3.10}$$

End-To-End Delay: When light propagates along a fiber, due to wavelength with different fiber composition (WFC), a delay is incurred per unit length, that is known as WFC dependent delay. According to [53] the WFC dependent delay, $D_{WFC}(i,j)$, per unit length of a link (i,j) can be expressed as

$$D_{WFC}\left(i,j\right) = a_f + b_f \times \lambda_l^2(i,j) + c_f \times \lambda_l^{-2}(i,j) \tag{3.11}$$

where a_f, b_f and c_f are fiber material dependent specific constants; $\lambda_l(i,j)$ is the l^{th} wavelength on link (i,j); $\lambda_l \in W(i,j)$; $l = \{1, 2, \ldots, N_\lambda\}$.
Equation (3.11) is also known as Sellmeier equation for delay computation. The ETED incurred of a link (i,j) with length $L(i,j))$ can be expressed as

$$ETED_c\left(i,j\right) = L\left(i,j\right) \times D_{WFC}\left(i,j\right) \tag{3.12}$$

The end-to-end wavelength dependent delay, $ETED_c(OVPNC^k(m,n,s,d))$, is the sum of individual link delays suffered by the k^{th} connection of (m,n) client with (s,d) pair. It can be derived as

$$ETED_c\left(OVPNC^k(m,n,s,d)\right) = \sum_{(i,j)\in OVPNC^k(m,n,s,d)} ETED_c\left(i,j\right) \tag{3.13}$$

where, $OVPNC^k(m,n,s,d)$ is the k^{th} OVPN connection.
Q-Factor: The computed Q-Factor value, QF_c for k^{th} OVPNC can be mathematically

represented as

$$QF_c\left(OVPNC^k(m,n,s,d)\right) = \frac{TDR_c(OVPNC^k(m,n,s,d))}{ETED_c\left(OVPNC^k(m,n,s,d)\right)} \tag{3.14}$$

3.3.1 Highest Q-Factor

The highest Q-Factor, $QF_h\left(m,n,s,d\right)$, is the maximum Q-Factor value of a k^{th} connection among the possible OVPNC. It can be expressed as

$$QF_h\left(m,n,s,d\right) = Max\left\{QF_c\left(OVPNC^k(m,n,s,d)\right)\right\},\ \forall k \tag{3.15}$$

where, $OVPNC^k(m,n,s,d) \in SOVPNC(m,n,s,d)$.

3.4 Functional Description of OVPN Control Manager

A generic functional block diagram of OVPNCM for the computation of Q-Factor is shown in Figure 3.4. The block digram basically has two modules: i) network layer module, and ii) a physical layer module. The network layer module deals with the computation of OVPNC. The physical layer module estimates the Q-Factor of an OVPNC. There are three stages in setting up a connection. In first stage, OVPNCM uses the traditional routing algorithm to compute all possible OVPNCs. Assuming that every fiber link has multiple fibers with different compositions. In second stage, it selects a better quality fiber material in order to get a good quality OVPNC. In third stage, OVPNCM computes the value of Q-Factor and the high quality OVPNC. Each section is explained below.

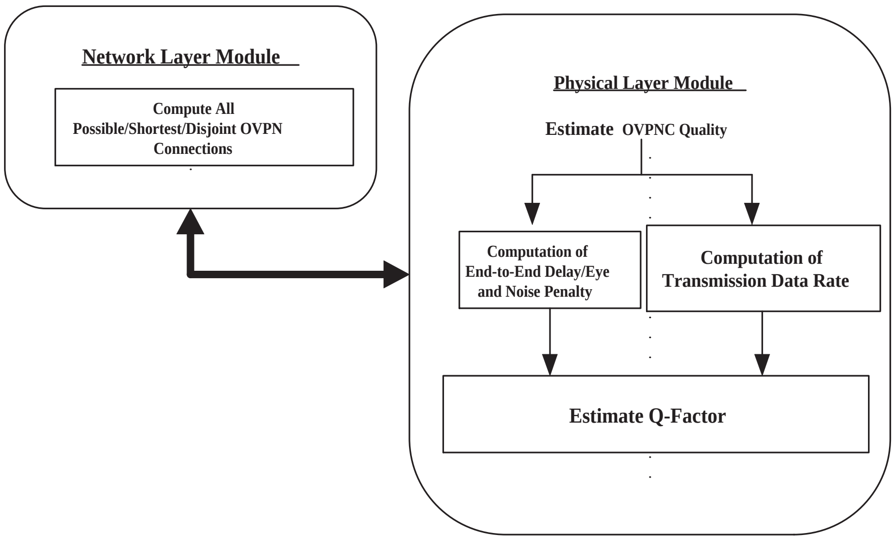


Figure 3.4: OVPN Control Manager

3.4.1 Computation of All Possible OVPNCs

To compute all possible OVPNC, we have modified the traditional depth-first search (DFS) algorithm [54]. Normally DFS algorithm is NP-Complete for the computation of all possible path, while considering multiple constraints. However, this computation uses single constraint i.e., path length.

Algorithm 3.1: *Compute_path*()

```
{Given data: source_node, destination_node, adjacency_matrix of the network
topology, no_of_nodes}
Global Initialization: n (Counter for Total_no_of_paths) = 1. Final_path = 0 (which
stores all possible paths)
Initialization: paths (temporary variable which stores updated paths for iterations
before computing all possible paths) = source_node
while paths! = 0 do
  Temp = 0 and [Total_no_of_paths, no_of_nodes] = size(paths)
  for i = 1 to Total_no_of_paths do
    current_node = paths (i, no_of_nodes)
    for k = 1, j = 1 to no_of_nodes do
      if (adjacency_matrix(current_node, j) == 1) then
        node_temp(k) = j
        k = k + 1
      end if
    end for
    path_temp = paths(i, :)
    Call the function path_temp2 with the arguments path_temp, node_temp which
    returns the path_temp1 matrix
    node_temp = 0
    if (length(path_temp1)! = length(path_temp)) and path_temp1! = 0 then
      if Temp! = 0 then
        Add the path_temp1 to temp matrix in a row
      else
        Temp = path_temp1
      end if
    end if
  end for
  paths = Temp;
end while
```

The modified path (connection) finding algorithm is explained in algorithm 3.1 and 3.2. The computation of path is done with the help of function *Compute_path*() mentioned in algorithm 3.1. *Path_temp*2 function in algorithm 3.2 receives the *path_temp* and *node_temp* matrix from the *Compute_path*() function and returns the temporary path matrix *path_temp*1. It is used to find all possible connections for a source-destination pair.

Complexity: The time occupation cost introduced in the modification of DFS algorithm is treated in a similar way as with the original DFS algorithm, which does not lead to much complexity. The time complexity of DFS is $O(n^2)$. However, in the modified DFS, the time complexity is $O(n^3)$, where n is the number of nodes in a network topology.

Algorithm 3.2: $Path\_temp2(path\_temp, node\_temp)$

```
{path_temp and node_temp values updates from Compute_path() function}
k = 1 and length = length(path_temp)
for i = 1 to length(node_temp) do
   for j = 1 to length do
      if path_temp(j) == node_temp(i) then
         node_temp(i) = 0
      end if
   end for
   if node_temp(i)! = 0 then
      if node_temp(i) == destination_node then
         Final_path(n, 1 : length) = path_temp(k, 1 : length)
         Final_path(n, length + 1) = node_temp(i)
      else
         path_temp(k, length + 1) = node_temp(i)
         k = k + 1
         path_temp(k, 1 : length) = path_temp(k − 1, 1 : length)
      end if
   end if
end for
if k == 1 then
   path_temp1 = 0
else
   path_temp1 = path_temp(1 : k − 1, :)
end if
Return path_temp1
```

3.4.2 Selection of Fiber Material

According to Equation (3.13), the delay in a connection depends on the type of fiber material as well as the wavelength. The deployment of fiber network backbone can use any type of fiber material depending on the usage and requirement of the network quality. We proposed a mechanism which computes the link or path quality of a fiber material in terms of delay. Based on the link or path delay values of various fiber materials, the mechanism selects the best one. The fiber material with different compositions, which provides minimal delay value during path computation is considered as the best quality material. The selection of fiber material can help for getting better quality OVPNCs.

Figure 3.5 presents the flowchart for this mechanism. It uses the the algorithm 3.1 to get M possible OVPNCs for a source-destination (s, d) pair. At the same time, it also takes K number fiber materials, N number of wavelengths per connection and finally uses the Equation (3.13) to estimate the ETED. The end computation gives a best suitable OVPNC.

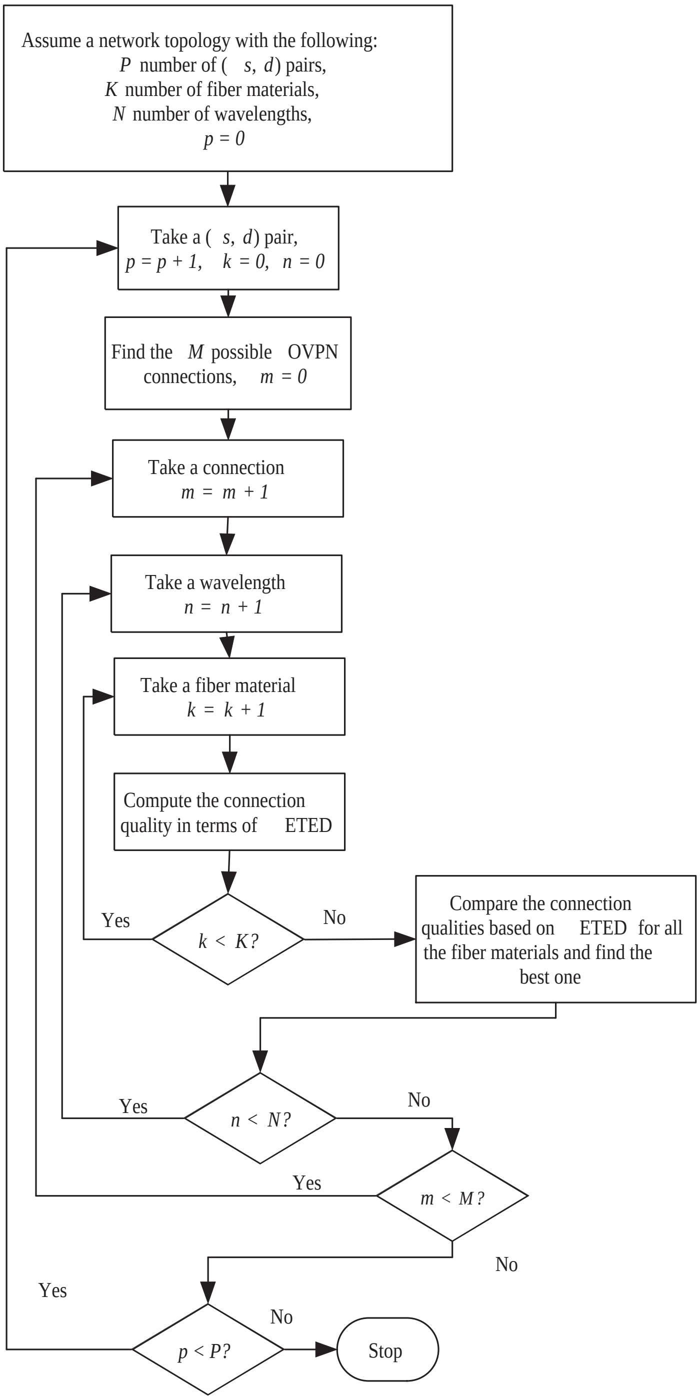


Figure 3.5: Flowchart for Fiber Material Selection

3.4.3 Computation of Q-Factor, High Quality OVPNC and Blocking Probability

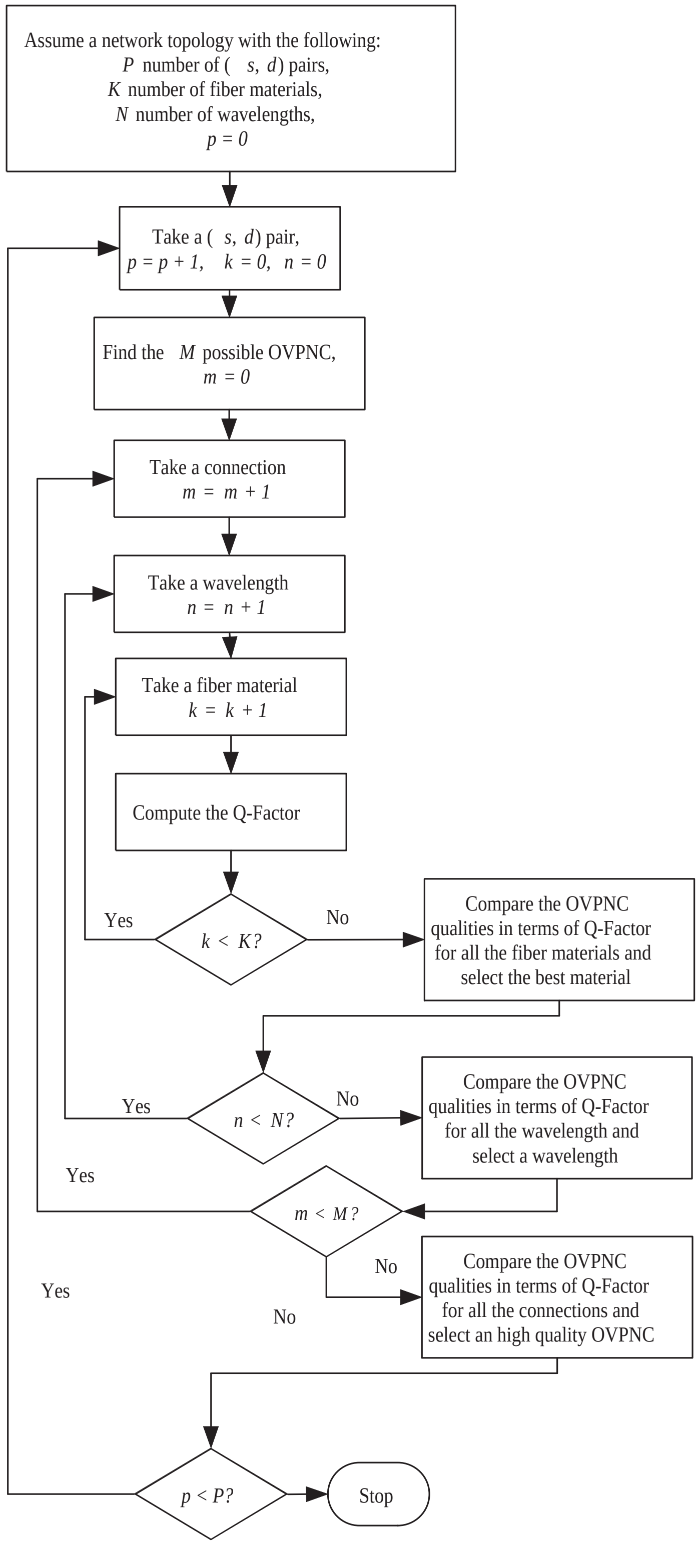


Figure 3.6: Flowchart for Computation of Q-Factor and High Quality OVPNC

We proposed a mechanism for the computation of Q-Factor and high quality OVPNC for a client request. The flowchart for this mechanism is shown in Figure 3.6. According to Equation (3.14), we have computed the Q-Factor value of a connection. By default, an high quality OVPNC is provided to the client, which is computed from the individual Q-Factor values of all possible OVPNCs. According to Equation (3.15), the mechanism computes an high quality OVPNC for which the Q-Factor value is highest among all the possible connections. The highest Q-Factor value can be provided to the client for highest level of satisfaction. Blocking probability is computed from the number of connections blocked with respect to the total number of connection requests from a particular connection pair attached to several clients. This will help to measure the performances of the proposed mechanism at different load (connection) sets. Assume $NP(m, n, s, d)$ is the total number of connection requested and $TNCB(m, n, s, d)$ is the total number of connection blocked for an (m, n) OVPN clients with (s, d) pair, then the blocking probability $BP(m, n, s, d)$ can be defined in percentage as

$$BP\left(m,n,s,d\right) = \frac{TNCB\left(m,n,s,d\right)}{NP\left(m,n,s,d\right)} \times 100 \tag{3.16}$$

3.5 Simulation Results and Discussion

The proposed QoS estimation technique is validated by simulation studies. An AON of 10 nodes and 16 links is considered as per NSFNet topology. This is a widely used benchmark network topology [3, 55, 56]. Following assumptions are made for simulation.

- All the nodes presented in the topology are of same types.
- All PER and OCR have same functionalities.
- All Links have same number of wavelengths for transmission.
- Wavelength continuity constrained is maintained for all OVPNCs.
- The value of PMD is same for all links.

Parameters considered for simulation is shown in Table 3.1. Three different fiber materials with the composition of aluminium-oxide, silicon-oxide and beta-barium borate are considered. A 10 nodes and 16 links NSFNet is considered for simulation. It is presented in Figure 3.7. The following sub-sections discuss the simulation results.

Table 3.1: Parameters Used for Simulation

Parameters	Values
Maximum number of wavelengths	8
Wavelength (λ) ranges in nm	1280 to 1360
Fit parameter (Aluminium-oxide)	a_f=1.5586, b_f=1.52365, c_f=0.010997
Fit parameter (Silicon-oxide)	a_f=1.30907, b_f=1.04683, c_f=0.01025
Fit parameter (Beta-barium borate)	a_f=1.46357, b_f=1.26172, c_f=0.01628
One fiber span	70km
Pulse broadening factor (δ)	0.1
Fiber PMD parameter ($DS_{pmd}(i,j)$)	0.2 $ps/(km)^{1/2}$

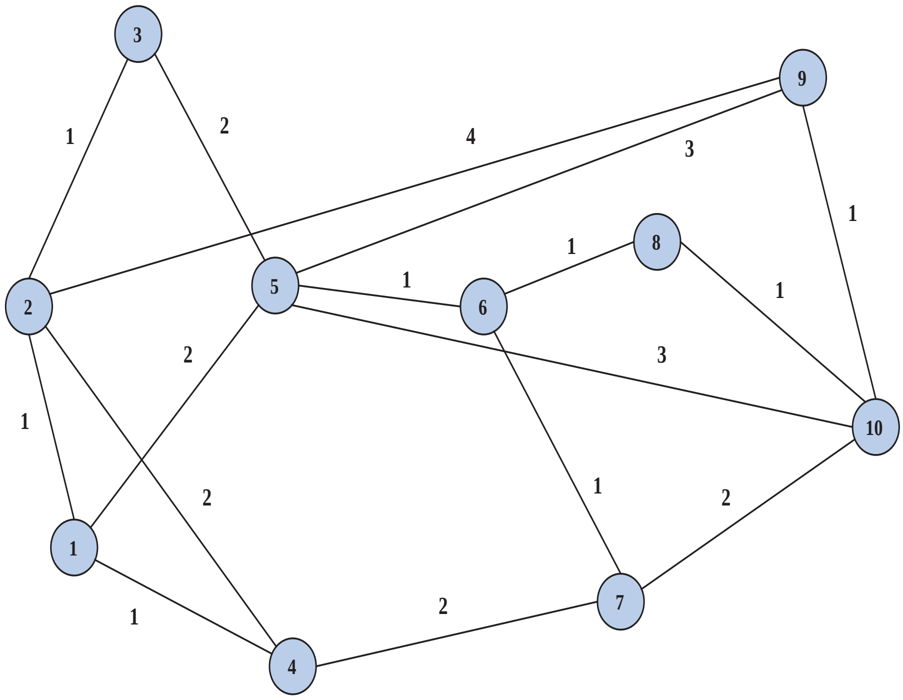
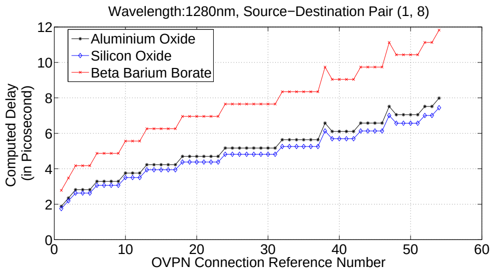


Figure 3.7: NSFNet Topology Used for Simulation, the number represents the number of spans, one span is 70km

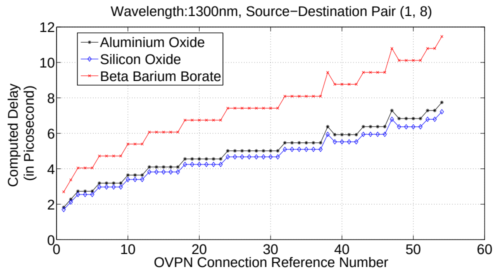
3.5.1 Fiber Material Selection

ETED is computed for all possible connections between a source-destination OVPN client pair. The simulation results for four pairs of source-destination (1, 8), (2, 9), (3, 7) and (4, 10) are considered. Figures (3.8 - 3.11) present the delay variations versus all possible OVPNC reference number (OVPNCRN) by taking different fiber materials and wavelengths for a given source-destination pair.

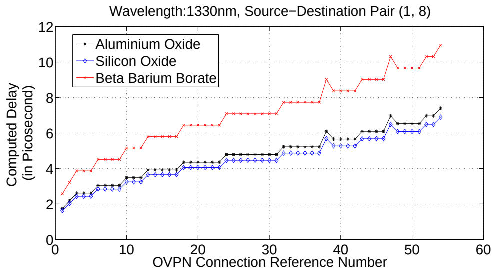
We noted OVPNC reference number instead of OVPNC index number. OVPNCRN is numbered based on the length of an OVPNC and arranged in incremental order. Figure 3.8(a), (b) and (c) present the variation of connection delays with respect to OVPNCRNs for a source-destination pair (1, 8) at wavelengths 1280nm, 1300nm and 1330nm respec-



(a) Wavelength: 1280nm.

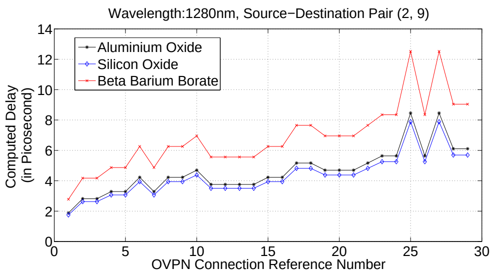


(b) Wavelength: 1300nm.

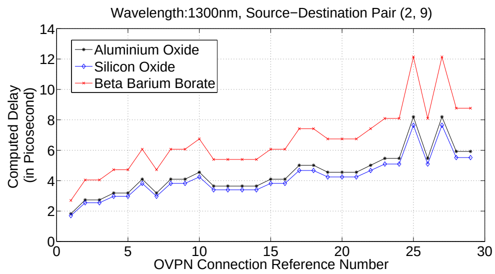


(c) Wavelength: 1330nm.

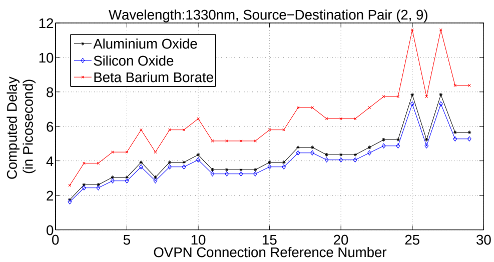
Figure 3.8: Computed Delay vs. OVPNCRN (Source:1, Destination:8).



(a) Wavelength: 1280nm.



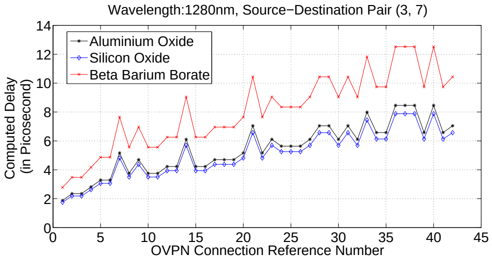
(b) Wavelength: 1300nm.



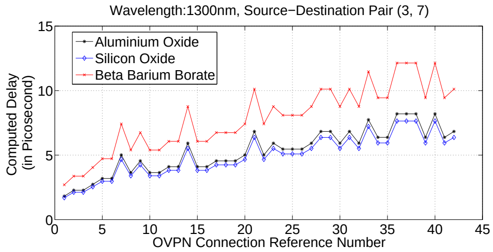
(c) Wavelength: 1330nm.

Figure 3.9: Computed Delay vs. OVPNCRN (Source:2, Destination:9).

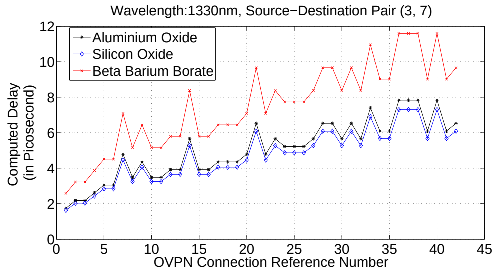
tively. The connection delays are computed for different fiber material compositions such as aluminium-oxide, silicon-oxide and beta-barium borate. Similar results are presented in Figure 3.9, 3.10 and 3.11. It is observed from these figures that the fiber with silicon-oxide composition incorporates the lowest delay. This leads to provide the best suited fiber for



(a) Wavelength: 1280nm.

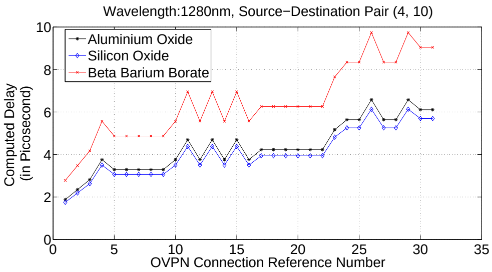


(b) Wavelength: 1300nm.

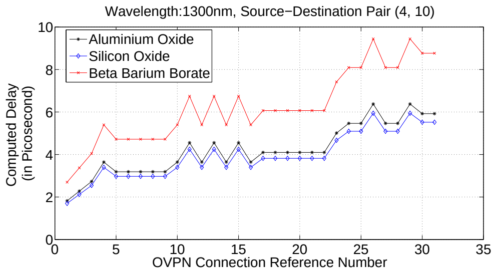


(c) Wavelength: 1330nm.

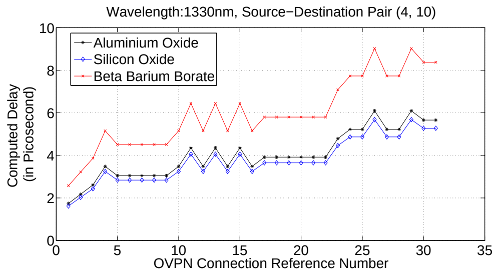
Figure 3.10: Computed Delay vs. OVPNCRN (Source:3, Destination:7).



(a) Wavelength: 1280nm.



(b) Wavelength: 1300nm.



(c) Wavelength: 1330nm.

Figure 3.11: Computed Delay vs. OVPNCRN (Source:4, Destination:10).

better quality OVPNC.

3.5.2 Q-Factor Based High Quality OVPN Selection

It is clear from the simulation results presented in previous section that the material with silicon-oxide composition has shown the highest quality as compared to others. For further comparison, the simulation based on Q-Factor dependent high quality OVPN selection has been performed again with the same source and destination pair. Q-Factor is computed for all possible connections between a source-destination OVPN client pair. Table 3.2 shows the simulation results for the computation of Q-Factor and the selection of high quality OVPNC of a source-destination pair (4, 10). From this tabular form, it will be easy to say that, which one will be the high quality OVPNC for a source-destination pair of an OVPN client. Figures 3.12 - 3.15 show the simulation results for the variation of computed Q-Factor versus OVPNCRN for (1, 8), (2, 9), (3,7) and (4, 10) OVPNC request

Table 3.2: Simulation for the Selection of High Quality OVPN Connection and Assigned Q-Factor, Wavelength: 1300nm

(s, d) Pair	Possible OVPNCs	OVPNCRN	Q-Factor (in %)	Selected OVPNC and Assigned Q-Factor
(4,10)	$4 \to 7 \to 10$	1	95.5396	$4 \to 7 \to 10$, 95.5396
	$4 \to 7 \to 6 \to 8 \to 10$	2	93.6093	
	$4 \to 1 \to 5 \to 10$	3	78.0078	
	$4 \to 1 \to 5 \to 6 \to 8 \to 10$	4	63.6931	
	$4 \to 2 \to 9 \to 10$	5	47.2798	
	$4 \to 1 \to 2 \to 9 \to 10$	6	66.8638	
	$4 \to 1 \to 5 \to 9 \to 10$	7	54.5941	
	$4 \to 7 \to 6 \to 5 \to 10$	8	47.2798	
	$4 \to 1 \to 5 \to 6 \to 7 \to 10$	9	54.5941	
	$4 \to 2 \to 1 \to 5 \to 10$	10	58.5058	
	$4 \to 2 \to 3 \to 5 \to 10$	11	47.7698	
	$4 \to 1 \to 2 \to 3 \to 5 \to 10$	12	58.5058	
	$4 \to 7 \to 6 \to 5 \to 9 \to 10$	13	47.7698	
	$4 \to 2 \to 1 \to 5 \to 6 \to 8 \to 10$	14	58.5058	
	$4 \to 2 \to 3 \to 5 \to 6 \to 8 \to 10$	15	47.7698	
	$4 \to 1 \to 2 \to 3 \to 5 \to 6 \to 8 \to 10$	16	47.7698	
	$4 \to 2 \to 1 \to 5 \to 9 \to 10$	17	52.0052	
	$4 \to 2 \to 3 \to 5 \to 9 \to 10$	18	42.4620	
	$4 \to 1 \to 2 \to 3 \to 5 \to 9 \to 10$	19	52.0052	
	$4 \to 2 \to 1 \to 5 \to 6 \to 7 \to 10$	20	42.4620	
	$4 \to 2 \to 3 \to 5 \to 6 \to 7 \to 10$	21	52.0052	
	$4 \to 1 \to 2 \to 3 \to 5 \to 6 \to 7 \to 10$	22	42.4620	
	$4 \to 1 \to 5 \to 3 \to 2 \to 9 \to 10$	23	30.0872	
	$4 \to 2 \to 9 \to 5 \to 10$	24	27.5799	
	$4 \to 1 \to 2 \to 9 \to 5 \to 10$	25	27.5799	
	$4 \to 2 \to 9 \to 5 \to 6 \to 8 \to 10$	26	27.5799	
	$4 \to 1 \to 2 \to 9 \to 5 \to 6 \to 8 \to 10$	27	27.5799	
	$4 \to 7 \to 6 \to 5 \to 1 \to 2 \to 9 \to 10$	28	27.5799	
	$4 \to 7 \to 6 \to 5 \to 3 \to 2 \to 9 \to 10$	29	27.5799	
	$4 \to 2 \to 9 \to 5 \to 6 \to 7 \to 10$	30	25.4584	
	$4 \to 1 \to 2 \to 9 \to 5 \to 6 \to 7 \to 10$	31	25.4584	

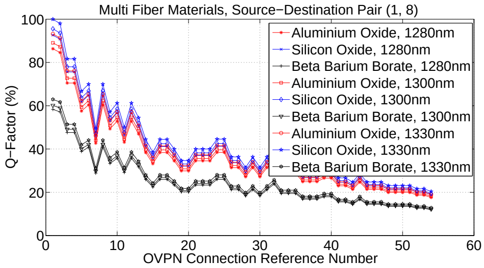
pairs.

For a given source-destination (s, d) pair, we varied the wavelength as well as the composition of fiber material and plotted the Q-Factor versus OVPNCRN. In Figure 3.12(a), (b) and (c), the results are presented for different fiber material compositions. From these figures, it is clear that, which OVPNC will have the highest Q-Factor value. By default, the connection corresponding to the highest Q-Factor value will be the high quality OVPNC for any connection requests. These plots clearly indicate about the effect of fiber composition during Q-Factor computation. In all the cases of fiber composition, silicon-oxide composition has shown the better Q-Factor value as compared to other compositions. Similar results are shown in Figure 3.13, 3.14 and 3.15.

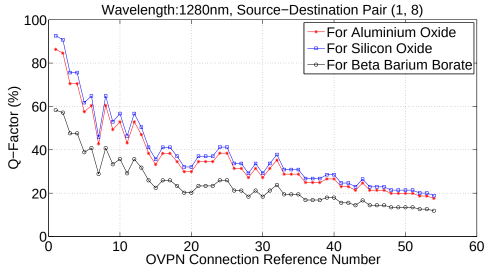
3.5.3 Blocking Probability

Blocking Probability is computed for all possible connections between a (s, d) OVPN client pair. The result for two pairs of source-destination (1, 8), and (2, 9) are taken. In this simulation, traffic pattern is considered in the form of OVPN connection requests, which is an uniform traffic pattern for all cases of simulation. It is expected that, similar result will apply when the traffic pattern changes. For a given (s, d) pair, we varied the wavelength, the composition of fiber material and number of OVPNC requests and plotted the blocking probability vs number of OVPNC requests. The Figures 3.16 and 3.17 show the simulation results for the connection blocking probability versus OVPNC requests for (1, 8) and (2, 9) OVPNC pairs at different wavelengths. In Figure 3.16(a), the blocking probability is taken at single wavelength. However, in Figure 3.16(b) and (c), the number of wavelengths are varied from 1 to 5 and 1 to 8 respectively. Similar results are shown in Figure 3.17 (a), (b) and (c). It is clear from these results that with increase in number of wavelengths per connection, the blocking probability decreases. The blocking probability performance also says that the fiber with silicon-oxide composition has shown the lowest blocking probability.

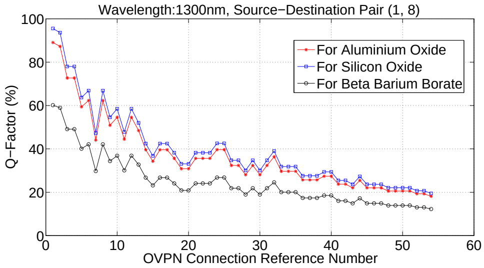
The simulations are taken by using the NSFNet topology, which has limitation of 10 nodes and 16 links. However, for larger network with more number of nodes, the number of possible OVPNCs mentioned in Table 3.2 will be more. The Q-Factor also can computed for any source-destination pair. In larger networks, the number of links for a source-destination pair can be very large. Under such circumstance, the computation of Q-Factor can be limited to 7 hops only. It is expected that, other routes will provide lower



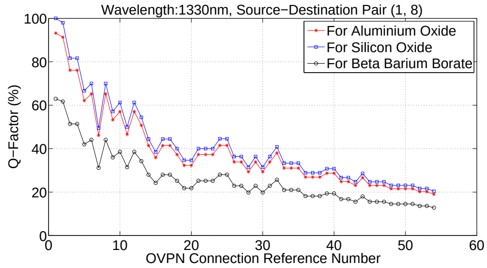
(a) Multiple wavelengths.



(b) Wavelength: 1280nm.

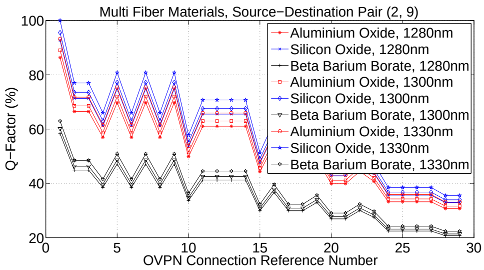


(c) Wavelength: 1300nm.

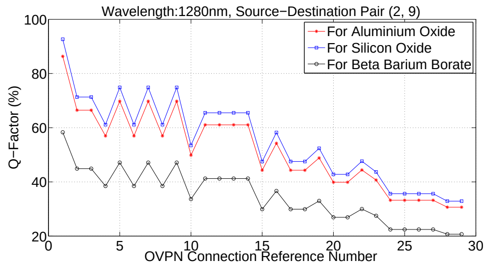


(d) Wavelength: 1330nm.

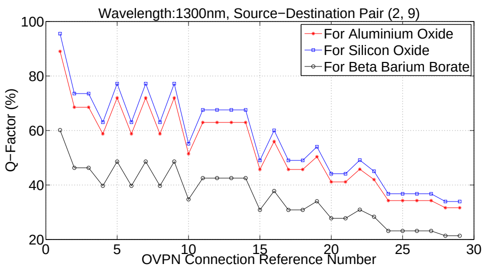
Figure 3.12: Q-Factor vs. OVPNCRN (Source: 1, Destination: 8).



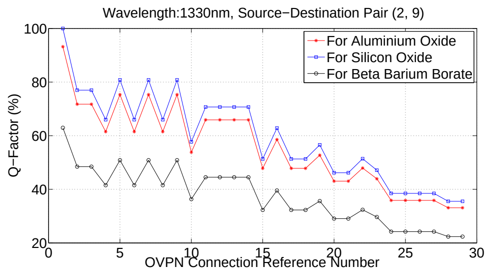
(a) Multiple wavelengths.



(b) Wavelength: 1280nm.

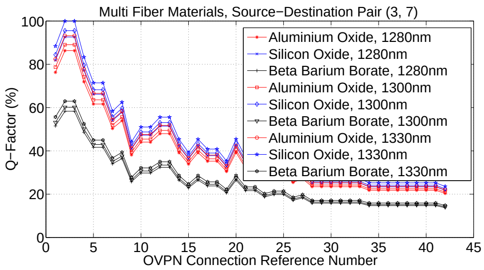


(c) Wavelength: 1300nm.

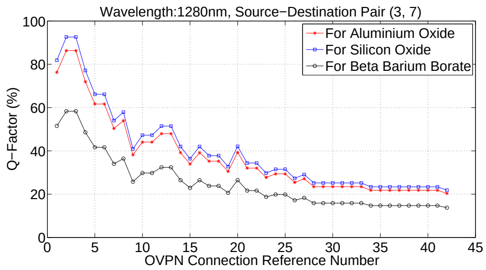


(d) Wavelength: 1330nm.

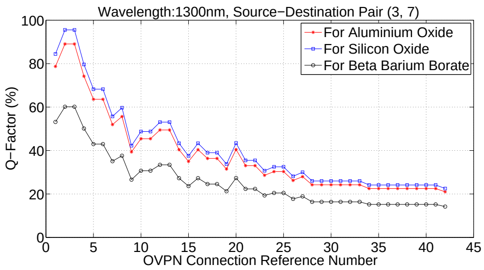
Figure 3.13: Q-Factor vs. OVPNCRN (Source: 2, Destination: 9).



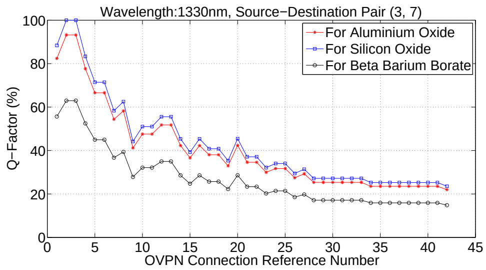
(a) Multiple wavelengths.



(b) Wavelength: 1280nm.

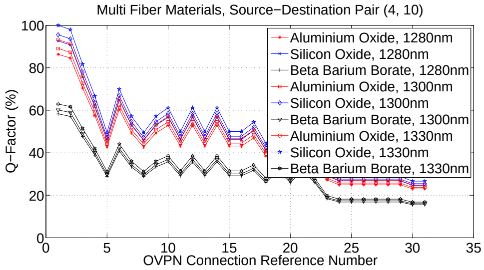


(c) Wavelength: 1300nm.

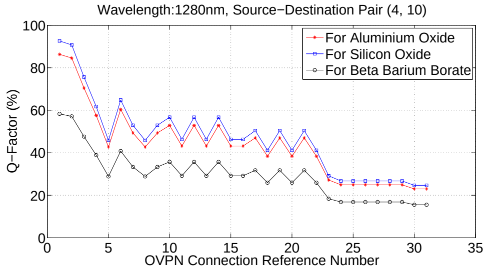


(d) Wavelength: 1330nm.

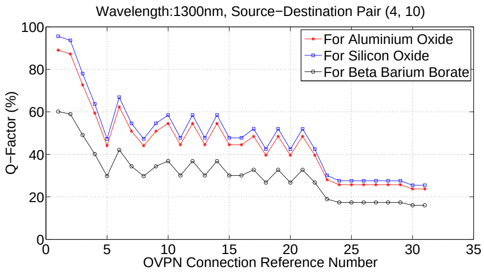
Figure 3.14: Q-Factor vs. OVPNCRN (Source: 3, Destination: 7).



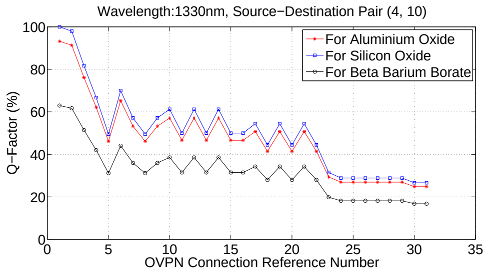
(a) Multiple wavelengths.



(b) Wavelength: 1280nm.



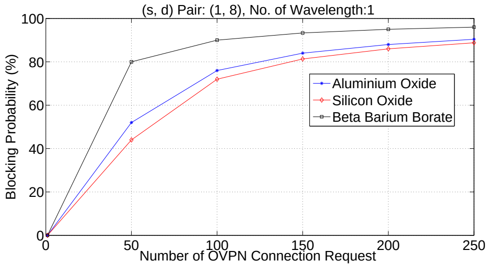
(c) Wavelength: 1300nm.



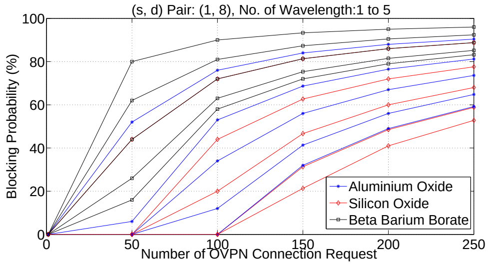
(d) Wavelength: 1330nm.

Figure 3.15: Q-Factor vs. OVPNCRN (Source: 4, Destination: 10).

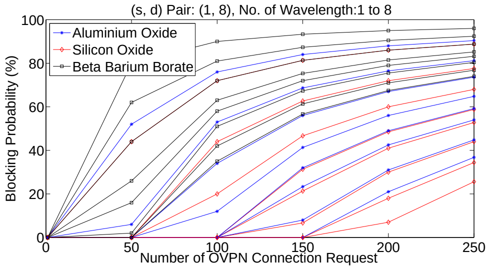
performance.



(a) No. of Wavelength: 1.

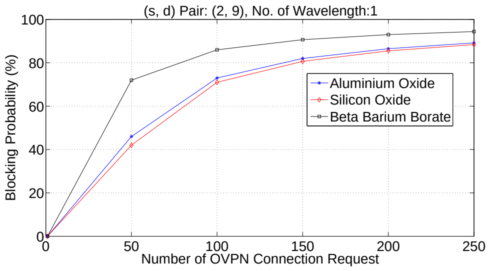


(b) No. of Wavelength: 1 to 5.

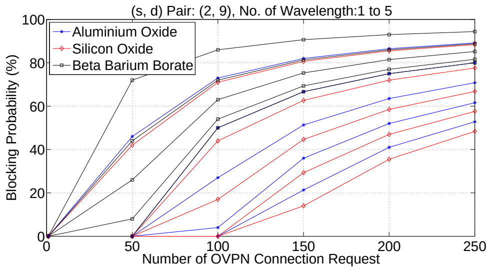


(c) No. of Wavelength: 1 to 8.

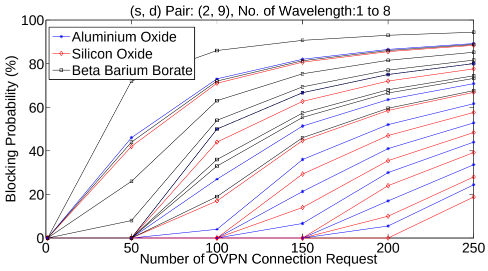
Figure 3.16: Blocking Probability vs. No. of OVPNC Requests (Multiple Fiber, Source: 1, Destination: 8).



(a) No. of Wavelength: 1.



(b) No. of Wavelength: 1 to 5.



(c) No. of Wavelength: 1 to 8.

Figure 3.17: Blocking Probability vs. No. of OVPNC Requests (Multiple Fiber, Source: 2, Destination: 9).

3.6 Conclusion

This chapter has discussed the motivation and a QoS based framework over WDM / DWDM network. Selection of fiber material for the high quality OPVNC is done based on i) wavelength dependent delay with different fiber material compositions, and ii) dispersion dependent transmission data-rate. This chapter has presented an algorithm that computes highest Q-Factor values among for all possible OVPNCs of a connection request. The performance analysis in terms of blocking probability clearly demonstrated the effect of fiber material with different compositions on connection quality. The fiber with Silicon Oxide composition can provide a better quality OVPNC due to its better performance in blocking probability. OVPNCM performs OVPN traffic engineering at the provider edge router, which manages the selection of high quality OVPNC. It also performs a global computation dynamically depending upon the OVPN traffic conditions i.e., number of OVPNC requests. The outcome of this computation is a decision criteria for the selection of an high quality OVPNC out of multiple connections. The proposed QoS framework is only for the control plane just before the data transmission, which will be helpful for quality based OVPNC selection for data transmission. The simulation study has been done using the benchmark NSFNet topology, which has a limitation of 10 nodes and 16 links.

CHAPTER 4

Total Dispersion Based Estimation of OVPN Connection Quality

Preface

In the previous chapter, the analysis of QoS was based on WFC dependent delay and TDR. It was used for selection of fiber material for the high quality OVPNC. This chapter analyses that the estimation of QoS based on delay is not only dependent on WFC but also on other parameters due to various dispersion effects. The computation of Q-Factor is done at OVPNCM by considering the effect of various dispersions and wavelengths on a fiber with silicon-oxide composition, which are prominent in high speed networks. The goal of this chapter is to dynamically select and assign a suitable OVPNC from a set of possible connections as per the QoS requirements of OVPN clients.

4.1 Introduction

Current research in optical network mostly concentrates on dynamic and quality based lightpath (OVPNC) setup mechanism. It is because of the increase in traffic load and the requirement of guaranteed signal quality [57]. This mechanism can satisfy the ever growing OVPN traffic demand from the end customer (client) and result in efficient utilization of the physical resources in the network [58].

OVPN over IP/GMPLS over WDM/DWDM technology with QoS assurances is considered as a promising approach in next generation OVPN [37, 59]. Now-a-days, WDM / DWDM network has become extremely popular technology among service providers, as they enable network capacity expansion without laying additional fibers. By using this technology, service providers can support several generations of optical technology without having to overhaul their fiber back bone networks as described in [60], and they can expand the capacity of any given optical link by simply upgrading the multiplexers and demultiplexers at each end. As a result, WDM/DWDM network has got a common place in service provider's core networks. As mentioned in [61], the GMPLS suite for routing and signaling protocols is currently the only technology that provides mechanisms for supporting the selection of connections in optical networks.

This chapter discusses an algorithm for the computation of OVPNC quality based on end-to-end total delay (ETETD). It occurs due to the effect of various dispersions in a fiber. These dispersions are the dominant impairment factors at high speed transmissions [8, 21, 46, 47]. At the time of efficient selection of OVPNC, various linear and non-linear impairment factors have to be considered. Without PLI awareness, an OVPNC selection algorithm cannot guarantee the desired performance. Some of the important LIs are PMD, group velocity dispersion (GVD), component cross talk, etc. and some of the important NLIs are FWM, SPM, XPM, scattering, etc. At high speed transmission PMD is one of the most dominant impairment factor in optical fiber [60]. In this case, two polarization state of fundamental mode may propagate at slightly different group velocities due to asymmetries in fiber, which results in pulse broadening of signal and affects in TDR.

The proposed mechanism computes the Q-Factor values of all possible OVPNCs based on various dispersion dependent ETETD and TDR. It also estimates the QoS requirement such as data-rate and delay from the client for an OVPNC in terms of required Q-Factor. Based on the computation of Q-Factor values, an algorithm has been proposed, that defines a mechanism for the effective selection of OVPNC by comparing the clients requirement and the availability of network resources.

4.1.1 Organization of the Chapter

The rest of the chapter is organized as follows. Section 4.2 gives the mathematical derivation of Q-Factor computation. The mechanism of OVPNC selection with wavelength assignment is discussed in Section 4.3. The proposed algorithm is presented in Section 4.4. The simulation results and discussion are described in Section 4.5. Finally, the work is concluded in Section 4.6.

4.2 Computation of Q-Factor

The OVPN system model mentioned in Figure 3.1 is considered for problem formulation and validation. It provides the layout pattern of interconnections of various elements like links, nodes, etc. of a network system. The physical topology explained in Figure 3.3 is followed. The selection of OVPNC can be based on required Q-Factor of the client and the availability of resources in the network, which are expressed as the computed Q-Factor. This section explains about various QoS parameters and the estimation of Q-Factor mechanism. The QoS parameters are normally fiber dispersion based TDR and ETETD. The estimation mechanisms of Q-Factor can be derived as a required Q-Factor in the client point of view or as a computed Q-Factor in the System (network) point of view. Section 4.2.1 presents in details about estimation of required Q-Factor.

4.2.1 Estimation of Required Q-Factor

The physical topology shown in Figure 3.3 is deployed for the estimation mechanism. In this figure, a number of connection requests for different applications are multiplexed at the source PER, s, to destination PER, d, for an OVPNC. The problem formulations can be based on different QoS requirements such as required data-rate (RDR) and delay in terms of required Q-Factor (RQF). It can be defined as the ratio of RDR to the ETETD of a connection (link). The RQF specifies the required connection quality of a connection request.

It is assumed that OVPN client end point is attached to at most one PER. In Figure 3.3, lets the application for an OVPN clients m and n with (s, d) pair be considered as required data-rate, $RDR(m, n, s, d)$, and required delay, $RD(m, n, s, d)$.

The required Q-Factor, $RQF(m, n, s, d)$ can be formulated as

$$RQF\,(m, n, s, d) = \frac{RDR\,(m, n, s, d)}{RD\,(m, n, s, d)} \tag{4.1}$$

where, $m \in \{1, 2, \ldots, M\}$ and $n \in \{1, 2, \ldots, N\}$; M and N are the total number OVPN clients attached to source, "s" and destination, "d" respectively. In a data plane, the application runs for multiple clients in single link/group of links (connection) but with different wavelengths tagging. The connection requests from any of the clients can be multiplexed as per the wavelength tagging.

4.2.2 Estimation of ETETD

Delay can occur in an OVPN system due to various effects such as CD, PMD, modal dispersion (MD), waveguide dispersion (WGD) and WFC. The details of derivations of delay computations is discussed in [16, 62–64] and presented below.

Delay due to the effect of CD: The time delay incurred in optical fiber link (i, j) due to CD can be expressed [16] as

$$D_{CD}\left(i, j\right) = DS_{CD}\left(i, j\right) \times L\left(i, j\right) \times \lambda_l\left(i, j\right) \tag{4.2}$$

where, $\lambda_l(i, j)$ is the available wavelength for the link (i, j); $\lambda_l\left(i, j\right) \in W\left(i, j\right)$; $l \in N_\lambda$; $DS_{CD}(i, j)$ is the CD coefficient; $L(i, j)$ is the link length.

Assuming $DS_{CD}(i, j)$ is same for all the cases of fiber links and hence, the relationship (4.2) can be written as

$$D_{CD}\left(i, j\right) = DS_{CD} \times L\left(i, j\right) \times \lambda_l\left(i, j\right) \tag{4.3}$$

Delay due to the effect of PMD: The differential time delay for a fiber link due to the effect of PMD can be expressed [16] as

$$D_{PMD}\left(i, j\right) = DS_{PMD}\left(i, j\right) \times \sqrt{L\left(i, j\right)} \tag{4.4}$$

where, $DS_{PMD}(i, j)$ is the PMD coefficient.

The PMD coefficient is assumed to be same for all the links and hence the relationship (4.4) can be written as

$$D_{PMD}\left(i, j\right) = DS_{PMD} \times \sqrt{L\left(i, j\right)} \tag{4.5}$$

Delay due to MD: The delay in a fiber link due to modal dispersion can be expressed [16] as

$$D_{MD}\left(i, j\right) = \frac{L\left(i, j\right) \times \left(n_1 - n_2\right) \times \left(1 - {}^{\pi}\!/_{V\left(i, j\right)}\right)}{C} \tag{4.6}$$

where, n_1 and n_2 are the refractive indices of core and cladding; C is the speed of light in vacuum and $V(i,j)$ is the frequency parameter of the fiber [56], which can be expressed for a wavelength $\lambda_l(i,j)$ as

$$V(i,j) = \frac{2 \times \pi \times a}{\lambda_l(i,j)} \sqrt{\left(n_1^2 - n_2^2\right)} \tag{4.7}$$

where, a is the diameter of the core.

Delay due to WGD: Time delay due to WGD can be represented [16, 65] as

$$D_{WGD}(i,j) = \frac{L(i,j) \times n_2 \times \Delta \times \nabla w}{C \times \lambda_l(i,j)} \times V(i,j) \times \frac{d^2\left(b\left(V(i,j)\right)\right)}{dV^2} \tag{4.8}$$

where, ∇w is the spectral width of the light source; b is the normalized propagation constant; $b(V(i,j))$ is the normalized frequency parameter of the fibers; Δ is the fractional refractive index difference and represented as

$$\Delta = \frac{(n_1 - n_2)}{n_1} \tag{4.9}$$

and $b(V(i,j))$ may be represented as

$$b\left(V(i,j)\right) = \frac{1 - \left(1 + \sqrt{2}\right)^2}{\sqrt{1 + \left(4 + V^4(i,j)\right)}} \tag{4.10}$$

Delay due to WFC: When a light propagates along a fiber link at certain wavelength with different fiber composition, a delay is incurred that is known as WFC dependent delay. It can be represented for a fiber link (i,j) pair as $D_{WFC}(i,j)$ and expressed as

$$D_{WFC}(i,j) = a_f + b_f \times \lambda_l^2(i,j) + c_f \times \lambda_l^{-2}(i,j) \tag{4.11}$$

where a_f, b_f and c_f are fiber material dependent specific constants, $\lambda_l(i,j)$ is the wavelength on link (i,j) and $\lambda_l \in W(i,j)$.

Computation of Total Delay (TD): The total root mean square (rms) delay incurred per unit length of a fiber link (i,j) due to the effect of CD, PMD, MD, WGD and WFC. It can be expressed [65] as

$$D_{TD}(i,j) = \sqrt{\left(D_{PMD}^2(i,j) + D_{CD}^2(i,j) + D_{MD}^2(i,j) + D_{WGD}^2(i,j) + D_{WFC}^2(i,j)\right)} \tag{4.12}$$

The ETETD incurred in a link (i, j) with length, $L(i, j)$, can be expressed as

$$ETETD_c\,(i, j) = L\,(i, j) \times D_{TD}\,(i, j) \tag{4.13}$$

The expression for ETETD for a k^{th} OVPNC can be written as

$$ETETD_c \left(OVPNC^k(m, n, s, d) \right) = \sum_{(i,j) \in OVPNC^k(m,n,s,d)} ETETD_c\,(i, j) \tag{4.14}$$

where, $OVPNC^k(m, n, s, d)$ is the k^{th} computed OVPNC for (m, n, s, d).

4.2.3 Estimation of TDR

Chapter 3 presented the concept that TDR of a link strongly depends on PMD. The expression of TDR is derived in Equations (3.8) and (3.10). For easy readability the relationship is presented here again.
The expression of TDR for the link (i, j) can be represented as

$$TDR(i, j) = \frac{\delta}{DS_{PMD} \times \sqrt{L(i, j)}} \tag{4.15}$$

The expression of TDR for a k^{th} OVPNC is derived as

$$\begin{aligned} &TDR_c(OVPNC^k(m, n, s, d)) = Min\{TDR(i, j)\}, \\ &\forall (i, j) \in OVPNC^k(m, n, s, d) \end{aligned} \tag{4.16}$$

where, $OVPNC^k(m, n, s, d) \in OVPNC(m, n, s, d)$.

4.2.4 Estimation of Q-Factor

Computation of Q-Factor is very important for the selection of quality based OVPNC. It can be computed for k^{th} OVPNC with a source-destination pair (s, d) as

$$QF_c \left(OVPNC^k(m, n, s, d) \right) = \frac{TDR_c \left(OVPNC^k(m, n, s, d) \right)}{ETETD_c \left(OVPNC^k(m, n, s, d) \right)} \tag{4.17}$$

where, m and n are clients.
The equation (4.17) represents the computed Q-Factor of an OVPNC.

4.3 Selection of OVPNC and Wavelength Assignment

In this section, proposed selection mechanism of OVPNC and wavelength assignment (OVPNCWA) is presented. The selection of an OVPNC is based on required and computed Q-Factor. If the RQF of an OVPNC request satisfies the computed Q-Factor of a connection, then the connection will be reserved by assigning an wavelength after checking its availability. If there is no available wavelength, then the request will be blocked, even though the connection satisfies the RQF. The following expression is for the mapping of the RQF with the computed Q-Factor for all possible OVPNCs.

$$RQF\,(m,n,s,d) \leq QF_c\left(OVPNC^k(m,n,s,d)\right), \forall k \tag{4.18}$$

The OVPNC request will be blocked for the following two conditions.

Case 1:

$$RQF\,(m,n,s,d) > QF_c\left(OVPNC^k(m,n,s,d)\right) \tag{4.19}$$

Case 2:

$$\lambda_l\,(m,n,s,d) = 0, \forall l \in N_\lambda \tag{4.20}$$

where, $\lambda_l(m,n,s,d)$ is the l^{th} wavelength on (s,d) pair and $\lambda_l(m,n,s,d) \in W(OVPNC^k(m,n,s,d))$, which is a wavelength vector of an OVPNC. In Equation (4.20), $\lambda_l(m,n,s,d)$ is the status of availability of wavelength at any of the connections between s and d. This says about the business of all the available computed connections, that states the non-availability of wavelength at any of the computed OVPNCs.

4.4 Proposed Algorithm

The OVPNCWA mechanism can be evaluated based on OVPNCM described in Figure 3.4. It considers three different OVPN connection types namely all possible (proposed) OVPN, shortest OVPN and disjoint OVPN. The proposed algorithm provides an OVPNC to the OVPN client depending on their RQF. Algorithm 4.2 states the OVPNCWA mechanism and the computation of blocking probability.

Algorithm 4.2 calls algorithm 4.1 to calculate the total number of OVPNCs of a source-destination pair. Algorithm 4.2 also calls algorithm 4.3 for the computation of OVPNC selection, assignment of Q-Factor, wavelength and computation of total number of connections accepted. Once the OVPNC is selected then the corresponding Q-Factor and wavelength will be assigned (reserved) for the required connection request. At the same time, it also computes the number of connections accepted, connections blocked and finally computes the blocking probability.

Complexity: In this case, depending on the number of nodes in a network topology time complexity can be analysed. The time occupation cost introduced in algorithm 4.2 is treated in a similar way as with algorithm 3.1. In this case, the time complexity is $O(n^7)$, where n is the number of nodes in a network topology.

Algorithm 4.1: Compute_Total_OVPNC

1: {Data: NT, N_λ,$AllPossibleOVPNC$, $ShortestOVPNC$, $DisjointOVPNC$, Result: HH}
2: **if** $nt = 1$ **then**
3: $HH = sizeof(AllPossibleOVPN)$
4: **else if** $nt = 2$ **then**
5: $HH = sizeof(ShortestOVPN)$
6: **else if** $nt = 3$ **then**
7: $HH = sizeof(DisjointOVPN)$
8: **end if**

Algorithm 4.2: OVPN_Selection_Wavelength_Assignment

{Data: Simulation network topology, Parameters for Simulation, SD, s, d, NT, NI, N_λ, RQF, NP, $cgroup$, Result: HH, $ETETD_c$, DR_c, QF_c, W, $TNCB$, $TNCA$ and BP }
Initialization: QF = [ ], cgroup = [1 15 25 50 100 150 200 250]
Compute $AllPossibleOVPNC$, $ShortestOVPNC$ and $DisjointOVPNC$
for $sd = 1 \rightarrow SD$ **do**
  for $nt = 1 \rightarrow NT$ **do**
    Compute HH
    for $hh = 1 : HH$ **do**
      for $l = 1 : N_\lambda$ **do**
        Initialize $w(hh, l)$
      end for
    end for
    for $ni = 1 \rightarrow NI$ **do**
      for $hh = 1 : HH$ **do**
        for $l = 1 : N_\lambda$ **do**
          Initialize $w(hh, l)$
          Compute $ETETD_c(hh, l)$
          Compute $TDR_c(hh, l)$
          Compute $QF_c(hh, l)$
        end for
      end for
      $NP = cgroup(ni)$
      for $k = 1 : NP$ **do**
        Select OVPNC
        Assign $Q - Factor$, $wavelength$ and Compute $TNCA$
      end for
      Compute $BP(nt, ni) = \frac{(NP - TNCA) \times 100}{NP}$
    end for
  end for
end for

Algorithm 4.3: Select_OVPNC_Assign_Q-Factor_Wavelength_Compute_TNCA

```
{Data: NP, HH, N_λ, W, RQF, QF_c, Result: Selected OVPNC, Assigned Q-Factor,
Assigned wavelength and bpc }
for k = 1 to NP do
   status(k) = 1
   for hh = 1 to HH do
      if status(k) = 1 then
      connection(k) is already checked
      else
      for l = 1 to N_λ do
         if RQF ≤ QF_c(hh, l) then
            connection(k) is accepted and OVPNC hh will be selected
            Assigned Q-Factor
            QF_c(hh, l) = 0
            Assigned wavelength is l
            w(hh, l) = 0
            status(k) = 1
            No. of connection accepted
            TNCA = TNCA + 1
            break
         else
            Reject connection(k)
         end if
         end if
      end for
   end for
end for
```

4.5 Simulation Results and Discussions

Following assumptions are made for simulation.

- All the nodes presented in the topology are of same types.
- All PER and OCR have same functionalities.
- All Links have same number of wavelengths for transmission.
- Wavelength continuity constrained is maintained for all OVPNCs.
- The value of PMD, CD, MD and WGD are same for all links.

Parameters considered in simulation is shown in Table 4.1. A fiber materials with the composition of silicon-oxide is considered. The spectral width (line width) is considered as 5nm, which is an acceptable value. A 10 nodes (routers) and 16 links NSFNet presented in Figure 3.7 is considered for simulation. In this simulation, traditional first-fit

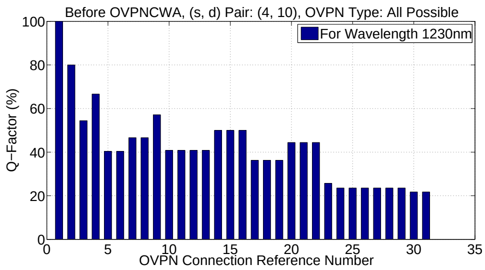
Table 4.1: Parameters Used for Simulation

Parameters	Values
Maximum number of wavelengths	8
Wavelength (λ) ranges in nm	1280 to 1360
Fit parameter (Silicon-oxide)	a_f=1.30907, b_f=1.04683, c_f=0.01025
One fiber span	70km
Spectral width (∇w)	5nm
Pulse broadening factor (δ)	0.1
PMD coefficient (DS_{PMD})	0.2 $ps/(km)^{1/2}$
CD coefficient (DS_{CD})	2.7 $ps/nm - km$

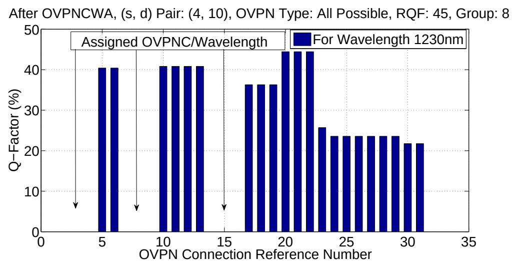
WA technique is employed along with Q-Factor assignment for a single or group of connection request. The proposed mechanism is analyzed by using three different OVPN types such as all possible, shortest and disjoint OVPN. All possible OVPN type is used and compared with other two traditional type of OVPNs. The attained results say that, how the OVPNCWA algorithm can help to assign a Q-Factor (wavelength) and compute the blocking probability for a given network. In order to get the best suitable connection, all the cases of OVPN types use Q-Factor as a quality parameter, which is the representation of TDR and ETETD. The following sub-sections discuss the simulation results.

4.5.1 Q-Factor and Wavelength Assignments

Figures 4.1 to 4.3 present the simulation results for Q-Factor with respect to OVPNCRN of an OVPN client source-destination pair (4, 10) with a RQF of 45 at single wavelength.



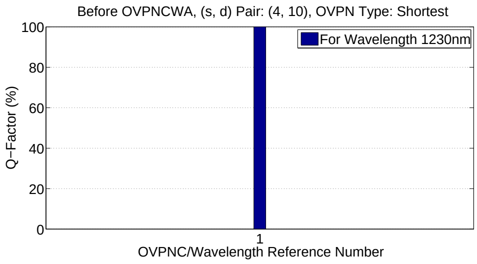
(a) Before OVPNCWA.



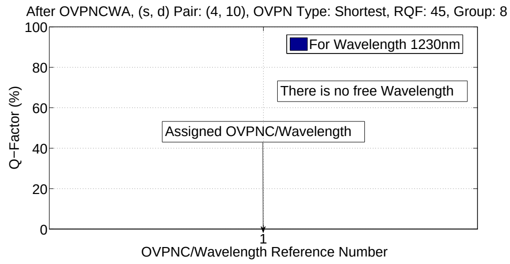
(b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.1: Q-Factor vs. OVPNCRN (All Possible OVPN, Source: 4, Destination: 10, No. of Wavelengths: 1).

In case of all possible OVPNs, it is observed that three connections are disjoint out of total 31 connections. The results are obtained by taking different wavelengths per connection. The OVPNCRN is an index assigned for an OVPNC. All the plots say about the OVPNC quality in terms of Q-Factor values before and after OVPNCWA. The Q-Factor

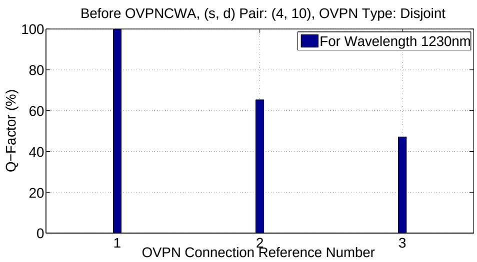


(a) Before OVPNCWA.

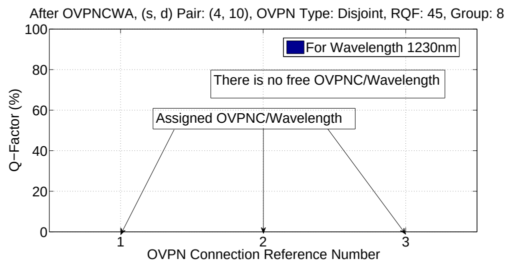


(b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.2: Q-Factor vs. OVPNCRN (Shortest OVPN, Source: 4, Destination: 10, No. of Wavelengths: 1).

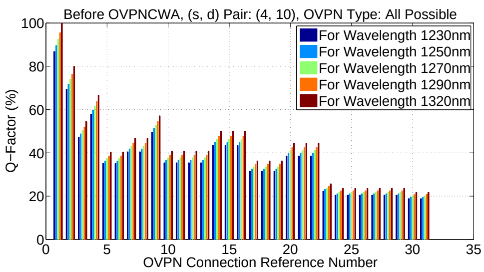


(a) Before OVPNCWA.

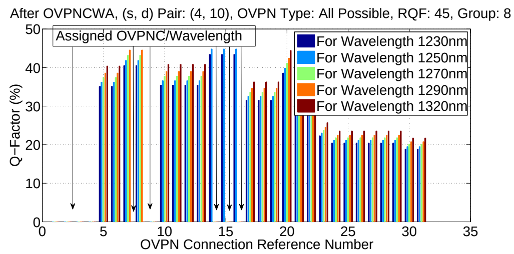


(b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.3: Q-Factor vs. OVPNCRN (Disjoint OVPN, Source: 4, Destination: 10, No. of Wavelengths: 1).



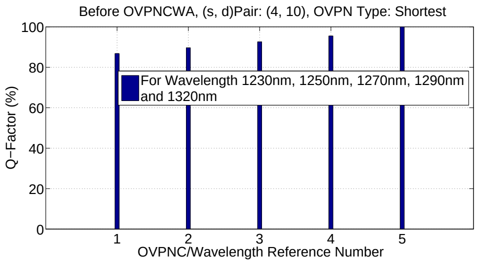
(a) Before OVPNCWA.



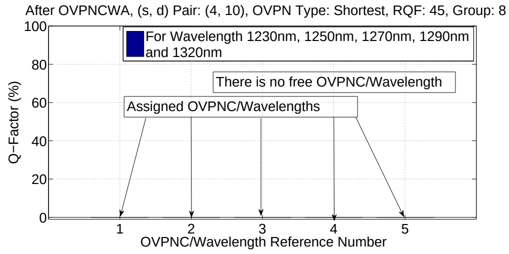
(b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.4: Q-Factor vs. OVPNCRN (Disjoint OVPN, Source: 4, Destination: 10, No. of Wavelengths: 5).

and WA to an OVPNC request are done by considering 8 number of OVPN connection request groups starting from group 1 to group 8, where group 1, group 2, group 3, group 4, group 5, group 6, group 7 and group 8 contains 1, 15, 25, 50, 100, 150, 200 and 250 number of connection requests respectively. The request groups are also known as Erlang in networking term. Erlang is the load (traffic) applied to the network. After wavelength and Q-Factor assignment as per OVPNC requirements, the Q-Factor values become zeros

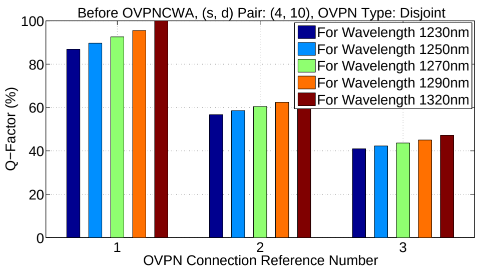


(a) Before OVPNCWA.

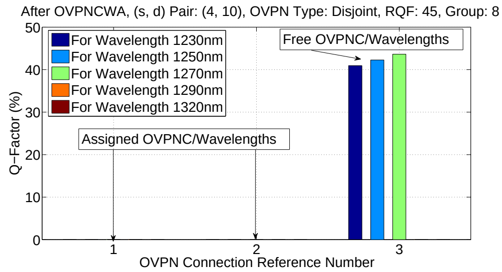


(b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.5: Q-Factor vs. OVPNCRN (Shortest OVPN, Source: 4, Destination: 10, No. of Wavelengths: 5).

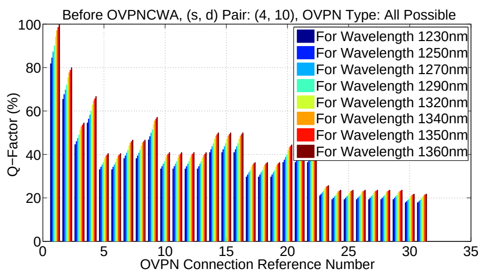


(a) Before OVPNCWA.

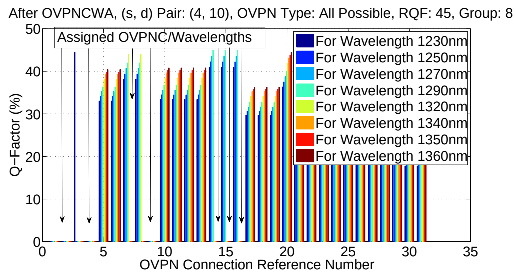


(b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.6: Q-Factor vs. OVPNCRN (Disjoint OVPN, Source: 4, Destination: 10, No. of Wavelengths: 5).



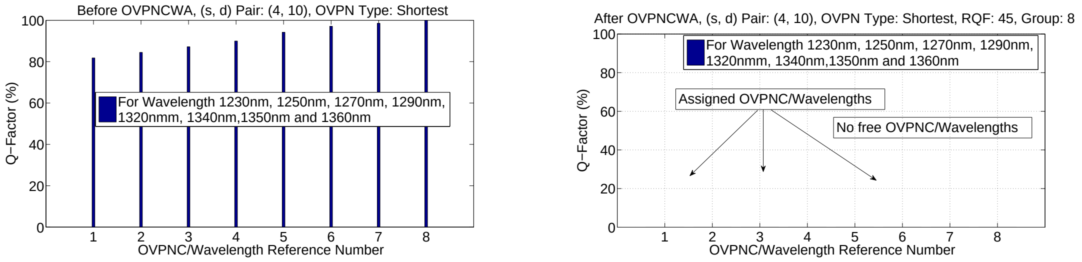
(a) Before OVPNCWA.



(b) After OVPNCWA for Group 8 with RQF 45.

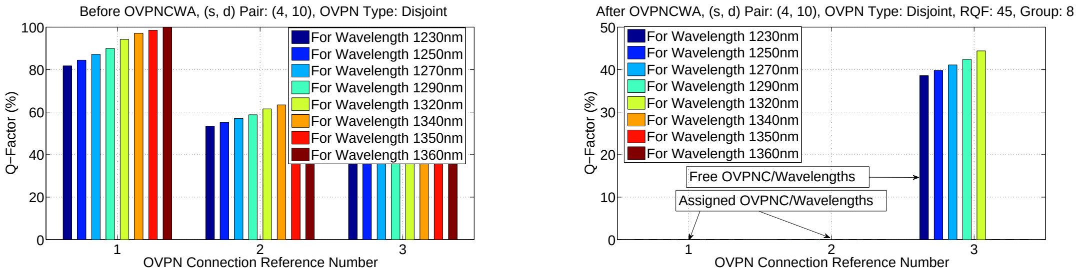
Figure 4.7: Q-Factor vs. OVPNCRN (All Possible OVPN, Source: 4, Destination: 10, No. of Wavelengths: 8).

for the respective connection requests. Let us take the example for the case of all possible OVPN type by taking 8^{th} group containing 250 connection requests with RQF of 45, where each OVPNC request will be assigned only one wavelength. For all possible OVPN case, the available Q-Factor values before connection requests and after connection requests are presented in Figure 4.1(a) and 4.1(b). It is clear from these plots that out of 250 connection requests only 10 are assigned to wavelengths and Q-Factor values and the remaining



(a) Before OVPNCWA. (b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.8: Q-Factor vs. OVPNCRN (Shortest OVPN, Source: 4, Destination: 10, No. of Wavelengths: 8).



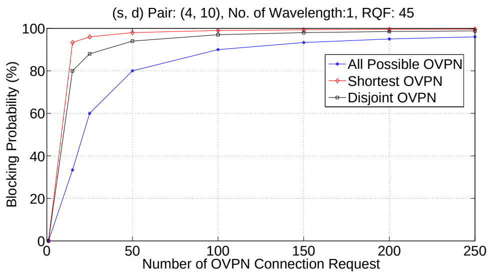
(a) Before OVPNCWA. (b) After OVPNCWA for Group 8 with RQF 45.

Figure 4.9: Q-Factor vs. OVPNCRN (Disjoint OVPN, Source: 4, Destination: 10, No. of Wavelengths: 8).

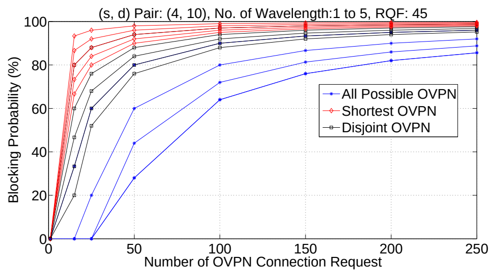
connections are blocked. In this case, the blocking probability will be (250 - 10)/250 = 0.96, which is 96 in percentage. Similar results are presented in Figure 4.4 to 4.9 with different wavelengths. With increase in number of wavelengths per connection, the availabilities of wavelengths (connections) increases. Due to this, more number of connection requests per group are accepted.

4.5.2 Blocking probability

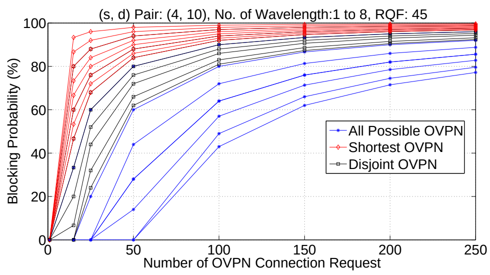
The Figures 4.10(a), 4.10(b) and 4.10(c) present the simulation results for the connection blocking probability with respect to the number of OVPNC requests of a source-destination pair (4, 10). In this simulation, an uniform traffic pattern in form of OVPN connection requests is considered. These plots are presented with variations of wavelengths for all possible, shortest and disjoint OVPNC types. All the plots show the comparison of all the OVPNC types. Shortest OVPN type has only one connection, which leads to high blocking probability of OVPN client request. The disjoint OVPN type has more number of connections and provides the client with more available resources. It is reasonable to say that the disjoint OVPN type can provide more OVPN connections and hence blocking probability is less as compared to shortest OVPN type. All possible OVPN type provides more connections and accordingly more number of wavelengths are available. It can lead to less blocking probability for a single or group of OVPNC requests as compared to the other two cases. A significant improvement in blocking probability is achieved by using all possible OVPN case. It can also be well understood that for all the cases, when the number of wavelength increases the blocking probability decreases. When the number of wavelength per connection increases, the blocking probability decreases significantly. In all cases, the performance of all possible OVPNC type shows better results with increase range of wavelengths.



(a) No. of Wavelength: 1.



(b) No. of Wavelength: 1 to 5.



(c) No. of Wavelength: 1 to 8.

Figure 4.10: Blocking Probability vs. No. of OVPNC Requests (Source: 4, Destination: 10, RQF: 45.)

4.6 Conclusion

This chapter presents a QoS estimation technique based on dispersion effects and uses it for the selection of OVPNC over WDM/DWDM network. We proposed an OVPN selection and WA mechanism by mixing of network and physical layer concepts in order to provide the end-to-end guaranteed OVPNC. The performance analysis is done in terms of blocking probability based on estimated Q-Factor. The QoS estimation technique has been evaluated for the selection of OVPNC by using three different OVPN types namely, shortest OVPN, disjoint OVPNs and all possible OVPNs. The proposed mechanism for the selection of OVPN is based on the required Q-Factor of the clients and the computed Q-Factor of the computed connections, which can provide a guaranteed OVPNC to the end clients. In principle, if the selection of OVPNC is being done based on the requirement of either TDR or delay, then the selected OVPNC might not be suitable for other requirements. In case of OVPNC selection based on Q-Factor, the selected OVPNC is expected to suit both the requirements.

CHAPTER 5

Noise and Eye Penalty Based Estimation of OVPN Connection Quality

Preface

In a WDM/DWDM network, LI constraints have high impact on connection quality. In the previous chapter, we have seen the effect of LIs on computation of link delays and TDR. The Q-Factor of an OVPNC was computed based on the above said parameters. This chapter deals with the noise and eye penalty based on the effect of LIs such as CD, PMD and ASE noise. A centralized controlled mechanism to estimate QoS in terms of Q-Factor based on noise and eye penalty is proposed here. The estimation technique is used for the selection of OVPNC out of multiple connections for any source-destination pair. This work also demonstrates the selection of OVPNC by assigning highest or required Q-Factor.

5.1 Introduction

Day-to-day growth in telecommunication network requires applications such as dynamic OVPN [36, 37] routing and re-routing with guaranteed QoS. The quality of OVPN routing in WDM/DWDM network not only depends on the network layer but also on the physical layer. The degradation of OVPNC quality occurs due to the effect of PLI constraints, which are broadly classified as linear and non-linear impairments [8]. The terms linear and non-linear in fiber optics mean intensity-independent and intensity-dependent impairments respectively. The LIs are static in nature and NLIs are dynamic in nature. The NLIs strongly depend on the current allocation of route and wavelength, i.e., on the current status of an allocated OVPNC. Moreover, the allocation of route and wavelength for a new OVPNC request affects the existing OVPNC in the network. Further, a guaranteed QoS based OVPNC requires a good control manager by the service provider. It should be applied at every router. We termed this as OVPNCM. It can be centralized or distributed. To obtain a guaranteed service for a client application, a centralized OVPNCM with network layer and physical layer impairment constraints are considered [22, 66] in this design. Such application might require a wide range of QoS guarantees from the service provider.

In this work, the computation of QoS for an OVPNC has been expressed in terms of LI based Q-Factor. The network model of Georgiadis et al. [67] and Glasmann et al. [68] is adopted with LI constraints. The main focus of this chapter is on LI constraints, which are defined as the parameter effect in the physical layer while establishing a source-destination connection. A LI model with a simple OVPNC selection mechanism is considered for a set of client applications. The objective is when and how to select an OVPNC for a single or group of connection requests at the access router. This problem can be solved by formulating a centralized mathematical control model for all the optical routers (ORs) based on the idea of differentiated services [35] to maintain the QoS for the incoming OVPN traffics.

5.1.1 Organization of the Chapter

The rest of the chapter is organized as follows. Section 5.2 gives the description of OVPN system model and problem formulation. The OVPN selection mechanism is discussed in Section 5.3. The Simulation results and discussion are described in Section 5.4. Finally, the work is concluded in Section 5.5.

5.2 OVPN System Model and Problem Formulation

We assumed a generic OVPN system model for problem formulation as mentioned in Figure 3.1. The physical topology mentioned in Figure 3.3 was adopted. Assuming the connectivity and wavelength availability in a system as mentioned in Equation 3.1 and 3.2 respectively, the problem of selection of OVPNC can be based on the required Q-Factor of the client and the availability of resources in the network in terms of computed Q-Factor.

The connection in an optical network involves with various LIs. The LIs have high impact on the overall network performance. In order to get a suitable OVPNC based on the link cost, it is needed to express LI constraints in terms of Q-Factors of a connection as mentioned in [69]. The link cost, $LC(i,j)$, for link (i,j) of a source-destination pair (s,d) can be expressed as

$$LC(i,j) = \frac{\sum_{k=1}^{N_\lambda(i,j)} 10\log\left[Q_i/Q_j\right]}{N_\lambda(i,j)} \tag{5.1}$$

where, $N_\lambda(i,j)$ is the total number of wavelengths at link (i,j); Q_i and Q_j are the Q-Factor measurements of i^{th} and j^{th} node respectively.
Further according to Tzanakaki et al. [70]

$$\frac{Q_i}{Q_j} = \frac{1}{\delta_{eye}\left(i,j\right) \times \delta_{noise}\left(i,j\right)} \tag{5.2}$$

where, $\delta_{eye}(i,j)$ and $\delta_{noise}(i,j)$ are the eye penalty and noise penalty at link (i,j) respectively.
Equation (5.1) can also be written as

$$LC(i,j) = \frac{\sum_{k=1}^{N_\lambda(i,j)} 10\log_{10}\left[\frac{1}{\delta_{eye}(i,j)\times\delta_{noise}(i,j)}\right]}{N_\lambda(i,j)} \tag{5.3}$$

Due to amplifier spans, the channel launch power can be relatively low without significant penalties due to the noise accumulation. The eye related penalty occurs due to the effect of linear physical impairments such as PMD and CD. The noise related penalty occurs due to the effect of ASE and crosstalk. The noise related penalty $\delta_{noise}(i,j)$ can be expressed as

$$\delta_{noise}\left(i,j\right) = \frac{p^j}{p^i} \times \frac{1}{\sqrt{F}} \tag{5.4}$$

where, p^i and p^j are the signal powers at i^{th} and j^{th} node respectively; F is the noise

figure; $p^j = p^i e^{-\alpha L(i,j)}$; α is the attenuation constant; $L(i,j)$ is the link length.
Equation (5.4) can be written as

$$\delta_{noise}\left(i,j\right) = \frac{1}{\sqrt{F}} \times e^{-\alpha L(i,j)} \tag{5.5}$$

The eye related penalty $\delta_{eye}(i,j)$ can be expressed as

$$\delta_{eye}\left(i,j\right) = \delta_{PMD}\left(i,j\right) \times \delta_{CD}\left(i,j\right) \tag{5.6}$$

where, $\delta_{PMD}(i,j)$ is the polarization mode dispersion factor and $\delta_{CD}(i,j)$ is the chromatic dispersion parameter.
δ_{PMD} can be derived from Equation (3.8) as

$$\delta_{PMD} = TDR(i,j) \times DS_{PMD}\left(i,j\right) \times \sqrt{L(i,j)} \tag{5.7}$$

Equation (5.6) also can be written as

$$\delta_{eye}\left(i,j\right) = TDR\left(i,j\right) \times DS_{PMD}\left(i,j\right) \times \sqrt{L\left(i,j\right)} \times \delta_{CD}\left(i,j\right) \tag{5.8}$$

where, $TDR(i,j)$ is the transmitted data-rate; $DS_{PMD}(i,j)$ is the PMD parameter; $L(i,j)$ is the link length.
Assuming $DS_{PMD}(i,j)$ and $\delta_{CD}(i,j)$ are same for all the links, Equation 5.8 can be represented as

$$\delta_{eye}\left(i,j\right) = TDR\left(i,j\right) \times DS_{PMD} \times \sqrt{L\left(i,j\right)} \times \delta_{CD} \tag{5.9}$$

Let us take k^{th} OVPN connection, $OVPNC^k(m,n,s,d)$ of (m,n) client with (s,d) pair for which the total connection cost, $TCC(OVPNC^k(m,n,s,d))$, can be expressed as

$$TCC\left(OVPNC^k\left(m,n,s,d\right)\right) = \sum_{(i,j)\in OVPNC^k(m,n,s,d)} LC(i,j) \tag{5.10}$$

The Q-Factor of k^{th} OVPN connection, $QF_c(OVPNC^k(m,n,s,d))$, can be defined as the inverse of the total connection cost. It can be mathematically written as

$$QF_c\left(OVPNC^k\left(m,n,s,d\right)\right) = \frac{1}{TCC\left(OVPNC^k\left(m,n,s,d\right)\right)} \tag{5.11}$$

where, $OVPNC^k(m,n,s,d) \in SOVPNC(m,n,s,d)$, which is a set of connections and represented as

$$SOVPNC(m, n, s, d) = \left\{OVPNC^1, OVPNC^2, ..., OVPNC^K\right\} \tag{5.12}$$

5.3 OVPN Selection Mechanism

OVPN Selection Mechanism can be evaluated based on OVPNCM mentioned in Figure 3.4. The selection mechanism helps to select an OVPNC from the available connections based on highest or required Q-Factor for an (m, n) client pair. First of all, a set of possible OVPNCs will be computed along with estimation of Q-Factor using algorithm 3.1 and Equation 5.11. Then, it will be decided whether to select the connection based on highest or required Q-Factor. The comparison takes decision for the selection of an OVPNC to the requested services. The two cases of OVPNC selection mechanism are explained as follows.

Case I: *Selection of OVPNC Based on Highest Q-Factor*

Assuming there are K number of possible OVPNCs with different Q-Factor values computed for an (m, n) client request with a source-destination pair (s, d). The connection among them with the highest Q-Factor value will be represented as the high quality OVPNC. In this case, the client needs only the best connection without any requirement (demand) of Q-Factor and accordingly OVPNCM assigns the high quality OVPNC to that client.

Let $QF_c(OVPNC^k(m, n, s, d))$ is the computed Q-Factor of k^{th} OVPNC. k is also known as the OVPNC reference (index) number and $k \in \{1, 2, 3...K\}$. The highest Q-Factor and OVPNC can be obtained from the following equation.

$$QF_h\left(m, n, s, d\right) = Max\left\{QF_c\left(OVPNC^k(m, n, s, d)\right)\right\},\ \forall k \tag{5.13}$$

Case II: *Selection of OVPNC Based on RQF*

In this case, client needs a connection with a RQF as per his application. The selection of OVPNC among the K number of possible connection will be based on the required Q-Factor for which only two different scenarios for the selection of OVPNC are considered.

Scenario 1: The RQF is less than or equal to the computed Q-Factor.

$$RQF\left(m, n, s, d\right) \le QF_c\left(OVPNC^k\left(m, n, s, d\right)\right), \forall k \in K \tag{5.14}$$

The connection, which satisfies the above equation will be selected for the client.

Scenario 2: The RQF is greater than the computed Q-Factor.

$$RQF\,(m,n,s,d) > QF_c\left(OVPNC^k\,(m,n,s,d)\right), \forall k \in K \tag{5.15}$$

If Equation 5.15 is satisfied, then the requested OVPNC will be blocked. If multiple connections are satisfied for a Q-Factor request, then the 1st shortest OVPNC will be assigned.

In both the above cases, the selection of OVPNCWA is done after checking the satisfaction level of Q-Factor.

5.4 Simulation Results and Discussion

Following assumptions are made for simulation.

- All the nodes presented in the topology are of same type.
- All PER and OCR have same functionalities.
- All Links have same number of wavelengths for transmission.
- Wavelength continuity constrained is maintained for all OVPNCs.
- The value of PMD and CD are same for all the links.

Parameters considered for simulation is shown in Table 5.1. A 10 nodes (routers) and 16 links NSFNet presented in Figure 3.7 is considered for simulation.

Table 5.1: Parameters Used for Simulation

Parameters	Values
Maximum number of wavelengths per link	8
Wavelength (λ) ranges in nm	1280 to 1360
One fiber span	70km
Pulse broadening factor (δ)	0.1
PMD coefficient (DS_{PMD})	0.2 $ps/(km)^{1/2}$
Attenuation Constant(α)	0.15dB
Chromatic dispersion (δ_{CD})	3000ps
Noise Figure(F)	0.4dB

In the simulation, Equations 5.14 and 5.15 are used for performance analysis, which indicates whether the requested OVPN service is accepted or blocked. The service accepted means the connection along with a wavelength will be assigned to the client and where as blocked means connection can't be provided due to unavailability of resources.

The following sub-sections discuss the simulation results.

5.4.1 Selection of OVPN Connection

The simulation results for the selection of OVPNCs with and without the required Q-Factor for a single or group of connection requests are described below. The simulation is done by taking three cases of OVPN type such as all possible, shortest and disjoint OVPN. Two cases of OVPN selection (assignment) mechanism mentioned in Section 5.3 are explained as follows.

Both the cases are considered for the selection of OVPNC and the result is presented. We have assumed a source-destination pair (4, 10) and presented the computation of OVPNCs with length for all possible, disjoint, and shortest OVPNCs in Table 5.2, Table 5.3 and Table 5.4 respectively. Here, each connection is assigned with a connection reference (index) number except shortest OVPN, whose reference numbers are taken based on number of wavelengths.

Table 5.2: Computation of All Possible OVPN Connections with Assigned Connection Reference Number

(s, d) Pair	Possible OVPNCs	OVPNCRN	Length of OVPNC (in km)
(4,10)	$4 \to 7 \to 10$	1	280
	$4 \to 7 \to 6 \to 8 \to 10$	2	350
	$4 \to 1 \to 5 \to 10$	3	420
	$4 \to 1 \to 5 \to 6 \to 8 \to 10$	4	420
	$4 \to 2 \to 9 \to 10$	5	420
	$4 \to 1 \to 2 \to 9 \to 10$	6	420
	$4 \to 1 \to 5 \to 9 \to 10$	7	420
	$4 \to 7 \to 6 \to 5 \to 10$	8	420
	$4 \to 1 \to 5 \to 6 \to 7 \to 10$	9	420
	$4 \to 2 \to 1 \to 5 \to 10$	10	560
	$4 \to 2 \to 3 \to 5 \to 10$	11	560
	$4 \to 1 \to 2 \to 3 \to 5 \to 10$	12	560
	$4 \to 7 \to 6 \to 5 \to 9 \to 10$	13	560
	$4 \to 2 \to 1 \to 5 \to 6 \to 8 \to 10$	14	560
	$4 \to 2 \to 3 \to 5 \to 6 \to 8 \to 10$	15	560
	$4 \to 1 \to 2 \to 3 \to 5 \to 6 \to 8 \to 10$	16	560
	$4 \to 2 \to 1 \to 5 \to 9 \to 10$	17	630
	$4 \to 2 \to 3 \to 5 \to 9 \to 10$	18	630
	$4 \to 1 \to 2 \to 3 \to 5 \to 9 \to 10$	19	630
	$4 \to 2 \to 1 \to 5 \to 6 \to 7 \to 10$	20	630
	$4 \to 2 \to 3 \to 5 \to 6 \to 7 \to 10$	21	630
	$4 \to 1 \to 2 \to 3 \to 5 \to 6 \to 7 \to 10$	22	630
	$4 \to 1 \to 5 \to 3 \to 2 \to 9 \to 10$	23	770
	$4 \to 2 \to 9 \to 5 \to 10$	24	840
	$4 \to 1 \to 2 \to 9 \to 5 \to 10$	25	840
	$4 \to 2 \to 9 \to 5 \to 6 \to 8 \to 10$	26	840
	$4 \to 1 \to 2 \to 9 \to 5 \to 6 \to 8 \to 10$	27	840
	$4 \to 7 \to 6 \to 5 \to 1 \to 2 \to 9 \to 10$	28	840
	$4 \to 7 \to 6 \to 5 \to 3 \to 2 \to 9 \to 10$	29	840
	$4 \to 2 \to 9 \to 5 \to 6 \to 7 \to 10$	30	910
	$4 \to 1 \to 2 \to 9 \to 5 \to 6 \to 7 \to 10$	31	910

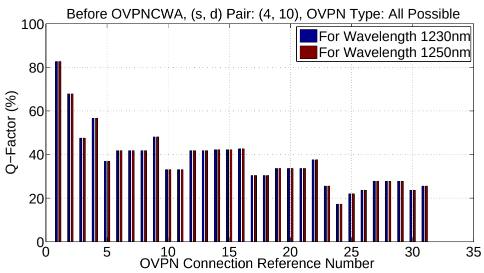
Table 5.3: Computation of Disjoint OVPN Connections with Assigned Connection Reference Number

(*s*, *d*) Pair	Disjoint OVPNCs	OVPNCRN	Length of OVPNC (in km)
(4,10)	$4 \rightarrow 7 \rightarrow 10$	1	280
	$4 \rightarrow 1 \rightarrow 5 \rightarrow 10$	2	420
	$4 \rightarrow 2 \rightarrow 9 \rightarrow 10$	3	420

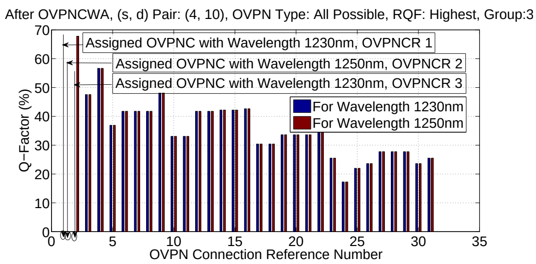
Table 5.4: Computation of Shortest OVPN Connection with Assigned Connection Reference Number

(*s*, *d*) Pair	Shortest OVPNC	OVPNC/Wavelength Reference Number	Length of OVPNC (in km)
(4,10)	$4 \rightarrow 7 \rightarrow 10$	1	280

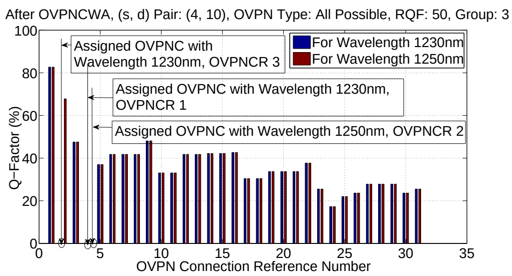
Figures 5.1 to 5.3 present the Q-Factor analysis for a source-destination pair (4, 10) at wavelengths 1230nm and 1250nm.



(a) Before OVPNC/Wavelength Assignment.



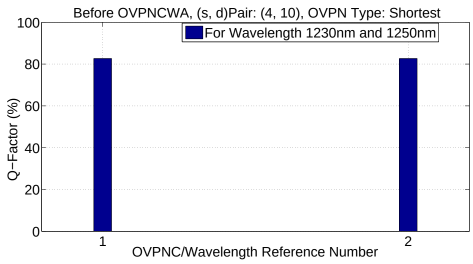
(b) After OVPNC/Wavelength Assignment, RQF: Highest.



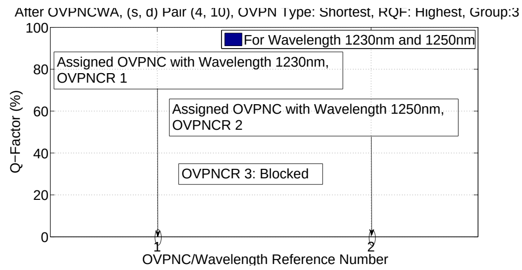
(c) After OVPNC/Wavelength Assignment, RQF: 45.

Figure 5.1: Q-Factor vs. OVPNCRN (All Possible OVPN, Source: 4, Destination: 10, No. of Wavelengths: 2, Group:3).

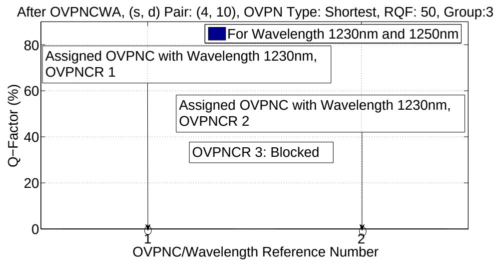
In all cases, the Q-Factor values are taken before and after the selection of OVPNC for a group of connection requests. Figure 5.1(a) shows the possible connection qualities when there is no requests from the clients. The available connections (wavelengths) are presented in this figure. The OVPNC request (OVPNCR) comes with a group, where a



(a) Before OVPNC/Wavelength Assignment.

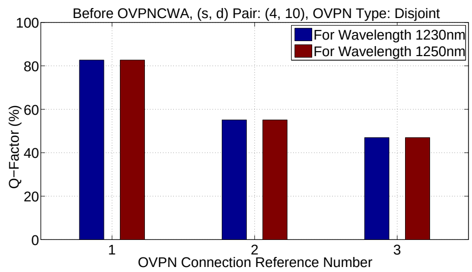


(b) After OVPNC/Wavelength Assignment, RQF: Highest.

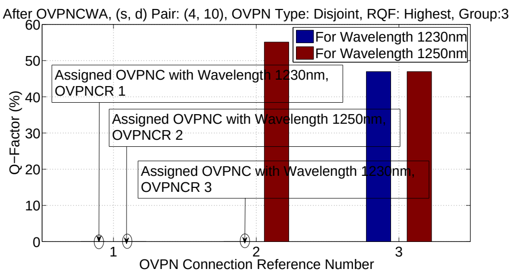


(c) After OVPNC/Wavelength Assignment, RQF: 45.

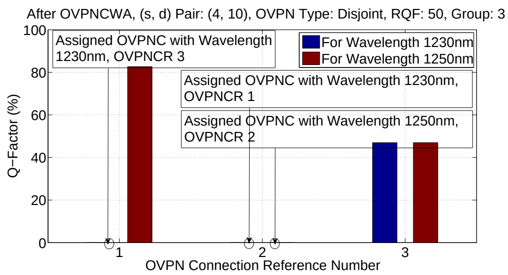
Figure 5.2: Q-Factor vs. OVPNCRN (Shortest OVPN, Source: 4, Destination: 10, No. of Wavelengths: 2, Group:3).



(a) Before OVPNC/Wavelength Assignment.



(b) After OVPNC/Wavelength Assignment, RQF: Highest.



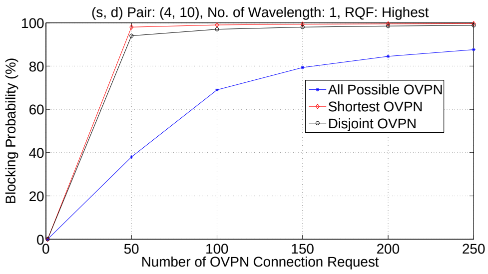
(c) After OVPNC/Wavelength Assignment, RQF: 45.

Figure 5.3: Q-Factor vs. OVPNCRN (Disjoint OVPN, Source: 4, Destination: 10, No. of Wavelengths: 2, Group:3).

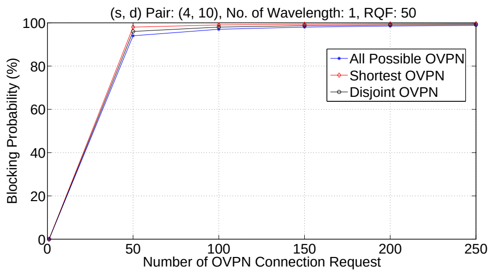
group may have multiple requests. The connection request are assigned based on highest or required Q-Factor, which are shown in figure 5.1(b) and 5.1(c) respectively. Similar results are shown in Figure 5.2 and 5.3 for shortest and disjoint OVPN case. When the RQF of a connection request is highest (maximum), an OVPNC with highest Q-Factor value among rest of the available connections is assigned. In other case, the RQF value has a specific value and based on that an OVPNC is assigned. It is clear from the results that most of the connections are assigned in case of all possible OVPN type for highest Q-Factor requirement.

5.4.2 Performance Analysis

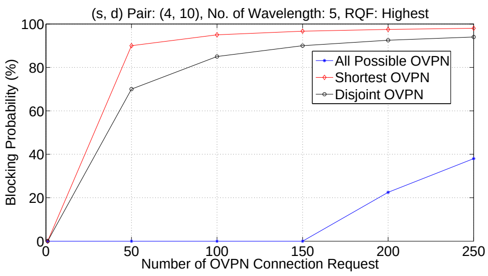
Figures 5.4(a) to 5.4(f) manifested the performance analysis in terms of blocking probability. This simulation uses an uniform traffic pattern in the form of OVPN connection



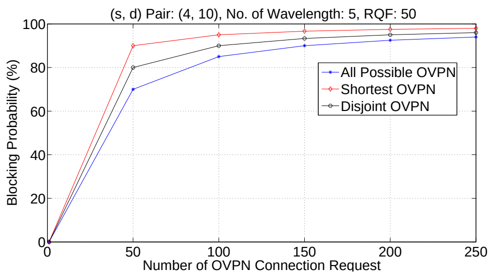
(a) No. of Wavelength: 1, RQF: Highest.



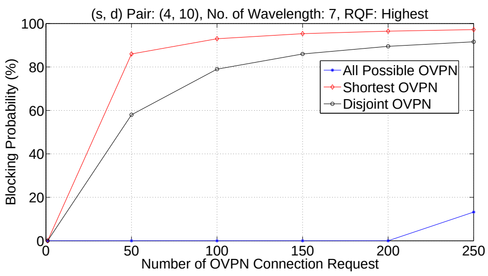
(b) No. of Wavelength: 1, RQF: 50.



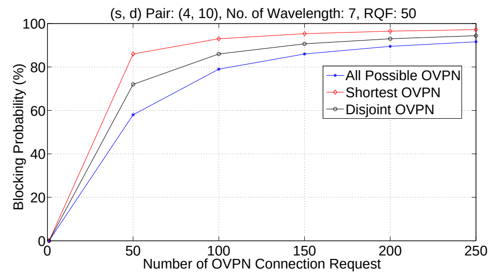
(c) No. of Wavelength: 5, RQF: Highest.



(d) No. of Wavelength: 5, RQF: 50.



(e) No. of Wavelength: 7, RQF: Highest.



(f) No. of Wavelength: 7, RQF: 50.

Figure 5.4: Blocking Probability vs. No. of OVPNC Requests (Source: 4, Destination: 10.)

requests. The simulations are taken for two of the cases mentioned in Section 5.3 by taking different wavelengths. Figures 5.4(a) and 5.4(b) are plotted with single wavelength. Similar results are presented in Figures 5.4(c) to 5.4(f) at different wavelengths. It is observed from these results that the blocking probability reduces when the number of wavelengths increases. The simulation results are shown for the selection of OVPNC for an OVPN client pair based on the highest and required Q-Factor. In both the cases, the performance analysis has been done rigorously. In Case I, an high quality OVPNC with highest Q-Factor value is assigned to the client. In Case II, an OVPNC is assigned as per the required Q-Factor. In case of highest Q-Factor and all possible OVPN type, the performance is better than other cases.

5.5 Conclusion

This chapter presents a LI based OVPN System model for the computation of OVPNC quality. We also proposed an OVPN selection mechanism for two cases of quality requirements such as highest and required Q-Factor of a connection request. The proposed mechanism has been demonstrated in the simulation results. During computation, multiple links are used to establish an OVPN connection. A link can have multiple spans of fiber, where each span is of 70km. Hence, a connection can be established with multiple spans of fiber, where re-generators or erbium-doped fiber amplifier (EDFA) is used for signal amplification at each span depending on its length. Today the best of the best fiber allows transmission up to 400km and after that it needs re-generators/EDFA. From the results, it can be concluded that, there are various ways of OVPNC selection mechanisms, but one out of those can be adopted based on the type of QoS requirements. The proposed mechanism is used by a centralized OVPN system, where the OVPNC information are analyzed and managed by the OVPNCM of a service provider. That's why the complete framework can be very useful for a service provider network.

CHAPTER 6

Hybrid Impairment Based Estimation of OVPN Connection Quality

Preface

The last chapter discussed the effects of LIs on noise and eye penalty, which were used for the computation of Q-Factor of an OVPNC. This chapter deals with the hybrid mixing effects of LIs and NLIs on connection quality (CQ). The presence of PLIs in high speed OVPN over WDM/DWDM network degrades the CQ. The CQ can be affected further by the increasing demand of connections and data speed. It is important to have an efficient OVPNCM to maintain the CQ. OVPNCM can ensure better quality of transmission to the OVPN clients. Traditional routing and RWA algorithms have less impacts on PLIs and cannot provide guaranteed OVPNC quality. In order to achieve a guaranteed CQ, we proposed a WA scheme and a hybrid crosstalk model based on linear IB and nonlinear FWM crosstalk. The hybrid crosstalk is used for the estimation of Q-Factor of an OVPNC. The performance of the proposed WA scheme with the hybrid crosstalk model is demonstrated. The results show that, the proposed hybrid crosstalk model with WA scheme not only provides a guaranteed OVPNC, but also improves the OVPN performance in terms of blocking probability.

6.1 Introduction

Network layer assumes that the physical layer is ideal, i.e. it does not have PLIs while making a routing decision. However, in reality the physical layer is never free from PLIs, which significantly affects the CQ during data transmission. In order to guarantee a CQ at the lightpath (OVPNC) level, a cross layer optimization method [21] should be adopted. RWA schemes in an OVPNC setup assume that the optical medium carries information with zero bit-error. However, in reality the transmission impairments occur due to the non-ideal nature of fiber components such as OXC, OADM etc. It may significantly affects the CQ. Sometimes signal is received with unacceptable bit-error rate (BER), which makes difficult to provide a desired quality to the connection request. Poor CQ necessitates to analyze the impact of impairments during the selection of OVPNC.

During the past few years, there has been extensive research on optical transparency and PLIs. Transparency leads to more economic and scalable networks without signal regeneration at the intermediate nodes. In a transparent network, data remain in optical domain between a source-destination pair. Noise and signal distortion due to PLIs accumulates as the signal travels through the OVPNCs and causes significant signal degradation. At the destination, the accumulated noise makes it unusable due to high BER.

In an optical network, the task of selecting an OVPNC is done at the network layer, which assumes that the underlying physical layer is ideal. Many PLI aware RWA algorithms have been proposed in the literature. We briefly describe few of them [21, 71–73]. Most of them have considered LIs because of simplicity and their effect on end-to-end connections might be estimated from link parameters, hence can be handled as a constraint on routing [8, 21]. There are few articles, where authors have taken only NLIs into consideration [48, 49, 69, 74] because of low complexity.

In the last few years, a lot of research have been carried out on PLI based routing algorithm. Huang et al. [21] considered ASE and PMD as PLIs and expressed the QoT in terms of OSNR. I. Tomkos et al. [69] proposed a Q-Factor model based on ASE, FWM and XPM. Similarly, N. Sengezer et al. [72] formulated a Q-Factor model by considering ASE, IB Crosstalk and PMD parameters. C. Politi et al. [74] proposed a Q-Factor model by using FWM, XPM and optical signal-to-noise ratio (OSNR) parameters. Ramamurty et al. [75] proposed the first PLI constrained based RWA algorithm taking ASE into consideration. They evaluated BER as the QoT parameter and allowed the lightpath that satisfies the threshold i.e., in terms of BER requirements.

In most cases, the probability density function of the overall noise is assumed to be

Gaussian due to its simplicity. However, the Gaussian model, despite its simplicity, cannot accurately describe the signal crosstalk noise, especially when the number of interfering channels are not very large. Though the central limit theorem is a good reason to use Gaussian approximation for reasonable large number of crosstalk, but for a small size mesh or ring network, where the number of crosstalk elements are small, this approximation gives inaccurate results. Therefore several non-Gaussian models have been developed for better estimation of system performance. Table 6.1 presents different approximations and assessment methods used by various authors with their applications as compared to our proposed model. It may be noted that, Gaussian, Gram-Charlier series and Saddle-point approximation methods are often computationally complex and take more time to evaluate the Q-Factor/BER during OVPNC selection. We have followed a simplified approach for Q-Factor calculation based on Taylor series expansions given by [76, 77] because of low complexity.

Table 6.1: Literature Survey

Authors Name	Model used	RWA Schemes	Remarks
K. Ho, 1999 [23]	Gram-Charlier series	Not considered	A Correction to Gaussian approximation
I. T. Monroy et al., 2006 [78]	Saddle-point approximation	Not considered	A Correction to to Gaussian approximation
S. D. Dods et al., 2005 [76]	Taylor series expansions	Not considered	Accurate model for low level crosstalk
S. Sarakar et al. [77]	Taylor series expansions with simplified approach	Not considered	Accurate and simple model for low level of crosstalk
J. He et al., 2010 [79]	Gaussian approximation	Considered	Simplest but found to be over estimating the system degradation especially when no. of crosstalk components are low

In this chapter, the hybrid impact of IB and FWM crosstalk on OVPNC quality is investigated. A WA scheme with the consideration of hybrid crosstalk is proposed for the selection of guaranteed OVPNC quality. The CQ is expressed in terms of Q-Factor and can be defined as the inverse of BER.

6.1.1 Organization of the Chapter

The rest of the chapter is organized as follows. Section 6.2 gives a brief discussion on the Crosstalk model. Hybrid crosstalk and WA dependent OVPNC selection mechanism are discussed in Section 6.3. The description of Proposed inner-outer band (PIOB) WA scheme is discussed in Section 6.4. The Simulation results and discussions are described in Section 6.5. Finally, the work is concluded in Section 6.6.

6.2 Crosstalk Model

The OVPN system model, layered pattern and physical topology mentioned in Figures 3.1, 3.2 and 3.3 respectively are considered here. In high-capacity optical networks, channels with multiple wavelengths are deployed to provide data-rate of the range of 10Gbps or higher per channel. Hence, the number of wavelengths per channel in a fiber has to be very large, but it is limited by the bandwidth of the optical devices, such as optical amplifier. For efficient use of the amplifier bandwidth, it is necessary to make the wavelength channel spacing closer.

Optical wavelength selective components along a lightpath generally have a limitation to distinguish the closely-spaced wavelength channels resulting in system impairment and crosstalk. Combined optical power of the wavelength channels is also so high that the fiber can no longer be treated as a linear medium. Crosstalk leads to significant degradation of signal quality and should be considered during RWA. Following this, the proposed hybrid crosstalk model is analysed. The proposed model is a mixture of linear IB and non-linear FWM crosstalk. For the sake of completeness, the following sub-section describes the IB and FWM crosstalk.

6.2.1 In-band Crosstalk

IB Crosstalk model is adopted from [73, 75–77, 80] with some modification. In WDM / DWDM network, data can be sent from one node to another node using a wavelength continuous route called OVPNCs without requiring any O/E/O conversion. Multiplexing, de-multiplexing and switching of signals are done in the optical domain using prisms and diffraction gratings. Non-ideal nature of these components generate IB crosstalk, which has the same wavelength as the signal degrading network transmission performance. IB crosstalk can be divided into coherent crosstalk, whose phase is correlated to the desired signal and incoherent crosstalk, whose phase is uncorrelated with the desired signal. Coherent crosstalk does not cause noise but causes a small fluctuation of signal power.

However, incoherent crosstalk has more adverse effect than the coherent crosstalk. The receiver model for this scenario is shown in Figure 6.1. An optical signal is detected by a square law detector (photo detector) followed by a matched filter. For each case of on/off keying, the integrated pulse energy is considered with a decision threshold value. Incoher-

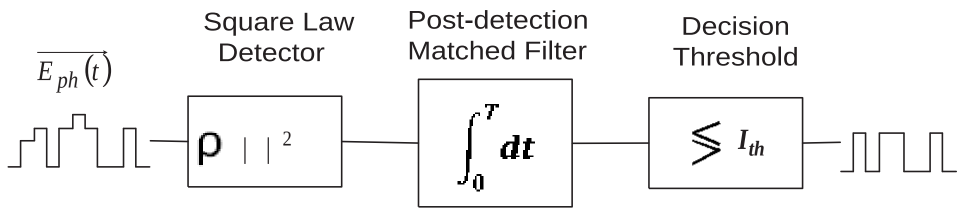


Figure 6.1: Receiver Model.

ent crosstalk is often analyzed using the probability density function, *pdf* of the noise in the received photo current. The *pdf* can be derived from the fields of the desired signal, $E_{ds}(t)$ and k^{th} interfering signal, $E_{\varepsilon,k}(t)$ as

$$E_{ds}\left(t\right) = \vec{r}_{ds} b_{ds}\left(t\right) \sqrt{P_{ds}} \exp\left[\left(j\omega_{ds}t + j\phi_{ds}\left(t\right)\right)\right] \tag{6.1}$$

$$E_{\varepsilon,k}\left(t\right) = \vec{r}_{k} b_{k}\left(t\right) \sqrt{\varepsilon_k P_{ds}} \exp\left[\left(j\omega_{k}t + j\phi_{k}\left(t\right)\right)\right] \tag{6.2}$$

where, $\omega_{ds,k}$ is the nominal optical angular frequency; $\phi_{ds,k}(t)$ represents the independent phase fluctuation of each optical source; $k \in \{1, 2, 3, \ldots, N\}$; N is the number of interfering signals (IB crosstalks); P_{ds} is the optical signal power of the received (desired) signal at the receiver; $\varepsilon_k = P_k/P_{ds}$ is the crosstalk level (relative power) of the k^{th} interfering signal to the desired signal; $b_{ds,k}(t)$ represents the binary symbols forming the amplitude modulated signal: $b_{ds,k}(t) \in \{0, 1\}$ depends on whether “0” or “1” is transmitted by the desired and interfering signal at time t; $\vec{r}_{ds,k}$ expresses the state of polarization of both the type of signals.

The total incident optical field, $E_{ph}(t)$ on the photo detector can be written for N crosstalk term as

$$E_{ph}\left(t\right) = E_{ds}\left(t\right) + \sum_{k=1}^{N} E_{\varepsilon,k}\left(t\right) \tag{6.3}$$

$$\begin{aligned} E_{ph}\left(t\right) &= \vec{r}_{ds} b_{ds}\left(t\right) \sqrt{P_{ds}} \exp\left[\left(j\omega_{ds}t + j\phi_{ds}\left(t\right)\right)\right] \\ &+ \sum_{k=1}^{N} \vec{r}_{k} b_{k}\left(t\right) \sqrt{\varepsilon_k P_{ds}} \exp\left[\left(j\omega_{k}t + j\phi_{k}\left(t\right)\right)\right] \end{aligned} \tag{6.4}$$

As it is known that, the instantaneous optical power is proportional to the squared magnitude of the electromagnetic field, from which the field intensity (photo current), $i_{ph}(t)$ received at the photo detector can be expressed as

$$i_{ph}\left(t\right) = \rho\left|E_{ph}\left(t\right)\right|^{2} \tag{6.5}$$

where, $\rho = \eta_q q_e / PE_{ph}$ represents detector (receiver) responsitivity; η_q is the quantum efficiency of the photo detector; q_e is the electron charge; and PE_{ph} is the photon energy.

For simplicity in analysis, assuming ρ of an ideal photo detector is unity. For worst-case assumption of identical polarization of the desired and interfering signal, the photo current, $i_{ph}(t)$ is given by

$$i_{ph}\left(t\right) \cong \left|E_{ph}\left(t\right)\right|^{2} \tag{6.6}$$

$$i_{ph}\left(t\right) \cong b_{ds}^{2}\left(t\right)P_{ds} + 2P_{ds}\sum_{k=1}^{N} b_{ds}\left(t\right)b_{k}\left(t\right)\sqrt{\varepsilon_k}\cos\vartheta_k\left(t\right) + P_{ds}\sum_{k=1}^{N} b_{k}^{2}\left(t\right)\varepsilon_k \tag{6.7}$$

$$i_{ph}\left(t\right) \cong b_{ds}^{2}\left(t\right)P_{ds} + \sum_{k=1}^{N} b_{ds}\left(t\right)b_{k}\left(t\right)A_k\cos\vartheta_k\left(t\right) + P_{ds}\sum_{k=1}^{N} b_{k}^{2}\left(t\right)\varepsilon_k \tag{6.8}$$

where, $\vartheta_k(t)$ is a random phase and $\vartheta_k(t) = \phi_k(t) - \phi_{ds}(t)$; $A_k = 2\sqrt{\varepsilon_k}P_{ds} = (2/\rho)\sqrt{\varepsilon_k}I_{ds}$.

Ignoring the small terms in the order of ε_k, the overall receiver noise $n_{ov}\left(t\right)$ in the photo detector is given by

$$n_{ov}\left(t\right) = \sum_{k=1}^{N} b_{ds}\left(t\right)b_{k}\left(t\right)A_k\cos\vartheta_k\left(t\right) + n_g\left(t\right) \tag{6.9}$$

where, $n_g(t)$ is the usual Gaussian noise in the receiver.

Assuming the extension ratio to be infinite so that, when a “0” is transmitted by the signal channel, there is no crosstalk and the noise will be

$$n_0(t) = n_g(t) \tag{6.10}$$

When a “1” is transmitted by the signal channel, crosstalk generates a total noise as

$$n_1\left(t\right) = \sum_{k=1}^{N} b_{k}\left(t\right)A_k\cos\vartheta_k\left(t\right) + n_g\left(t\right) \tag{6.11}$$

For N interfering signals and Gaussian noise, the *pdf* of the noise in the received photo current can be obtained by integrating the Gaussian noise over all possible values of phase offset between desired and each interfering signal. Assuming the phase difference between these signals are independent and uniformly distributed between (0, π), then the *pdf* for noise photo current, $p_{n,k}(y)$ is given by

$$p_{n,k}\left(y\right)=\frac{1}{\sqrt{2\pi\sigma^{2}}\pi^{N}}\times\left[\int_{0}^{\pi}..\int_{0}^{\pi}\exp\left[-\frac{\left\{y-\sum\limits_{k=1}^{N}A_{k}\cos\vartheta_{k}\right\}^{2}}{2\sigma^{2}}\right]d\left(\vartheta_{1}\right)..d\left(\vartheta_{N}\right)\right] \tag{6.12}$$

where, σ^2 is the variance of receiver thermal noise; σ is the receiver thermal noise power.

The effect of IB crosstalk is maximum, when phase difference is close to 0 and the *pdf* can be approximated by expanding the cosine term by first order Taylor series up to the term ϑ_k^2 as

$$p_{n,k}\left(y\right)=\frac{1}{\sqrt{2\pi\sigma^{2}}\pi^{N}}\times\left[\int_{0}^{\pi}..\int_{0}^{\pi}\exp\left[-\frac{\left\{y-\sum\limits_{k=1}^{N}A_{k}\left(1-\frac{\vartheta_{k}^{2}}{2}\right)\right\}^{2}}{2\sigma^{2}}\right]d\left(\vartheta_{1}\right)..d\left(\vartheta_{N}\right)\right] \tag{6.13}$$

Expanding the square term and keeping terms up to ϑ_k^2, the *pdf* for noise during transmission of “1” is given by

$$p_{n,k}\left(y\right)=\frac{1}{\sqrt{2\pi\sigma^{2}}}\left\{\prod_{k=1}^{N}f\left(y\right)\right\}\exp\left[-\frac{\left(y-\sum\limits_{k=1}^{N}A_{k}\right)^{2}}{2\sigma^{2}}\right] \tag{6.14}$$

$$f\left(y\right)=\sqrt{\frac{\sigma^{2}}{2\pi A_{k}\left(y-\sum\limits_{k=1}^{N}A_{k}\right)}}erf\left[\pi\sqrt{\frac{A_{k}\left(y-\sum\limits_{k=1}^{N}A_{k}\right)}{2\sigma^{2}}}\right] \tag{6.15}$$

where, $erf(....)$ is the error function.

In the presence of IB crosstalk BER is given by the fraction of the received photo current *pdf*’s that fall on the wrong side of the decision variable, I_{th} called the detection threshold for each combination of data “1”s and “0”s of the desired and interfering signal. The detection threshold is defined as the half of the photo current (I_{ds}). For extreme case, when all the interfering signals transmit “1”, the upper bound of BER can be set. The corresponding bit-error probability, p_{be}^{inb}, for the IB crosstalk can be expressed using

Bayes' theorem as

$$p_{be}^{inb} = \frac{1}{2}p_{be0} + \frac{1}{2}\left[\frac{1}{2}p_{be1}\left(b_k = 0\right) + \frac{1}{2}p_{be1}\left(b_k = 1\right)\right] \tag{6.16}$$

where,

$$p_{be0} = \frac{1}{2}erfc\left(\frac{I_{th}}{\sqrt{2\sigma_0^2}}\right) \tag{6.17}$$

$$p_{be1}\left(b_k = 0\right) = \frac{1}{2}erfc\left(\frac{I_{ds} - I_{th}}{\sqrt{2\sigma_0^2}}\right) \tag{6.18}$$

$$p_{be1}\left(b_k = 1\right) = \frac{1}{2^{N+1}}\left\{\prod_{k=1}^{N} f\left(I_{ds} - I_{th}\right)\right\}\sum_{k=1}^{N} erfc\left\{\frac{\left(I_{ds} - \sum\limits_{k=1}^{N} A_k - I_{th}\right)}{\sqrt{2\sigma_1^2}}\right\} \tag{6.19}$$

$$\sigma_1 = \sigma_0\sqrt{\left(1 + 4N\epsilon_k\left(SNR_{inb}\right)^2\right)} \tag{6.20}$$

and

$$SNR_{inb} = \frac{I_{th}}{\sigma_0} \tag{6.21}$$

where, the weighting function, $f(y)$ is approximated as $f(I_{ds} - I_{th})$ to make the integral possible; $erfc(....)$ is the complimentary error function; σ_1^2 is the variance of the receiver thermal noise when "1" is transmitted by the signal channel; σ_0^2 is the variance of the receiver thermal noise when "0" is transmitted; and SNR_{inb} is the signal-to-noise ratio in case of IB crosstalk.

Now the expression for p_{be}^{inb} at the WDM receiver can be expressed as

$$\begin{aligned} p_{be}^{inb} &= \tfrac{1}{4}erfc\left(\tfrac{I_{th}}{\sqrt{2\sigma_0^2}}\right) + \tfrac{1}{8}erfc\left(\tfrac{I_{ds}-I_{th}}{\sqrt{2\sigma_0^2}}\right) \\ &+ \tfrac{1}{2^{N+3}}\left\{\prod_{k=1}^{N} f\left(I_{ds} - I_{th}\right)\right\}\sum_{k=1}^{N} erfc\left\{\frac{\left(I_{ds} - \sum\limits_{k=1}^{N} A_k - I_{th}\right)}{\sqrt{2\sigma_1^2}}\right\} \end{aligned} \tag{6.22}$$

where, $I_{ds} = \rho P_i$, P_i is the input power.

6.2.2 Four-Wave Mixing Crosstalk

The FWM crosstalk model [81–83] is used for the estimation of FWM power. It is further required for the computation of FWM noise power. For high optical power in a WDM/DWDM system, the refractive index of a fiber will depend on the optical intensity of signals propagating through the fiber. Generally in most of the time, the intensity modulation i.e., on/off keying (OOK) is used for the optical transmission to maintain a constant signal fluctuation. This fluctuation causes change in the refractive index of the fiber, which results in a phase variation between two intermediate wavelength channels and produces optical crosstalk known as cross-phase modulation. The variation of refractive index not only induces phase shift within the channel but also generates new signals with new wavelengths. It is known as FWM crosstalk. This crosstalk type may impair the system performance significantly.

The effect of FWM crosstalk is independent of the bit rate of the system and critically dependent on the channel spacing and CD of the fiber. FWM crosstalk effect is inversely proportional to the channel spacing. It occurs when two or more signals of different wavelengths propagate simultaneously and interact with the nonlinear dielectric fiber medium. The effect of FWM generates a set of new wavelengths within the range of operating wavelengths. It is always present in an optical network. However, it becomes prominent in new generation optical networks because of few main reasons such as use of high intensity signal, high density channels and use of low CD shifted fiber.

In case of equally spaced channels with wavelengths λ_p, λ_q and λ_r, a new FWM component $\lambda_{p,q,r}$ will be generated. It can be expressed as

$$\lambda_{p,q,r} = \lambda_p + \lambda_q - \lambda_r \tag{6.23}$$

where, $p \neq r$ and $q \neq r$. The newly generated wavelength lies within the operating wavelength range and can affect network performance due to the IB crosstalk generation and power reduction in the same nominal wavelength. If there are n number of available operating wavelengths, then M number of FWM components will be generated, which can be represented by

$$M = \frac{n^2\,(n-1)}{2} \tag{6.24}$$

The FWM power, $P_{pqr}(i,j)$ is generated in an optical link (i,j) due to the presence of wavelengths λ_p, λ_q and λ_r. It can be denoted as

$$P_{pqr}(i,j) = \frac{\eta}{9} d^2 \gamma^2 P_p P_q P_r e^{-\alpha L} L_{eff}^2 \tag{6.25}$$

where, p, q, and r are the wavelength index number; d is the degeneracy factor, which is 3 for $(\lambda_p = \lambda_q)$ and 6 for $(\lambda_p \neq \lambda_q)$; P_p, P_q, and P_r are the input powers for the signals with wavelength channels λ_p, λ_q and λ_r respectively; L is the fiber length; α is the fiber attenuation coefficient; γ is the non-linear coefficient and L_{eff} denotes the effective fiber length, which is represented as

$$L_{eff} = \frac{\left(1 - e^{-\alpha L}\right)}{\alpha} \tag{6.26}$$

The efficiency η of the FWM can be represented as

$$\eta = \frac{\alpha^2}{\alpha^2 + \beta_{pqr}^2} \left[1 + \frac{4e^{-\alpha L} sin^2(\beta_{pqr} L/2)}{(1 - e^{-\alpha L})^2}\right] \tag{6.27}$$

According to [84] η can also be approximated to

$$\eta = \frac{\alpha^2}{\alpha^2 + \beta_{pqr}^2} \tag{6.28}$$

where, $\eta = 1$, if $\beta_{pqr} = 0$; β_{pqr} is the phase-matching factor and also known as propagation constant difference, which depends on channel spacing and fiber CD and can be calculated as

$$\begin{aligned} \beta_{pqr} &= 2\pi c \lambda_k^2 \Delta\lambda_{pq} \Delta\lambda_{qr} \\ &\times \left[D_c + (\tfrac{\lambda_k^2}{2})(\Delta\lambda_{pq} + \Delta\lambda_{qr}) \tfrac{dD_c(\lambda_k)}{d\lambda}\right] \end{aligned} \tag{6.29}$$

where, λ_k is the central wavelength; $\lambda_{mn} = |\lambda_m - \lambda_n| m, n = p, q, r$; c is the speed of light; D_c is the fiber chromatic dispersion; $\frac{dD_c(\lambda_k)}{d\lambda}$ is the dispersion slope.
When β_{pqr} is away from the zero dispersion region, it can be represented as

$$\beta_{pqr} = 2\pi c \lambda_k^2 D_c \Delta\lambda_{pq} \Delta\lambda_{qr} \tag{6.30}$$

For an equally spaced channels i.e., $\Delta\lambda_{pq} = \Delta\lambda_{qr} = \Delta\lambda$, β_{pqr} will be discrete and can be represented as

$$\beta_{n_{ef}} = 2\pi n_{ef} c \lambda_k^2 D_c \Delta\lambda^2 \tag{6.31}$$

where, $n_{ef} = |p - r||q - r|$ is the efficiency order; $\Delta\lambda$ is the wavelength difference between two channels and typically a multiple of 0.4nm.

It is known that, k^{th} OVPNC for a source-destination pair, (s, d) goes through multiple links, so the total FWM power for the connection will be accumulative and can be expressed as

$$P_{pqr}(s, d) = \sum_{(i,j) \in OVPNC^k(s,d)} \sum_p \sum_q \sum_r P_{pqr}(i, j) \tag{6.32}$$

where, $SOVPNC(s, d)$ is a set of connection for a (s, d) pair, that can be expressed as

$$SOVPNC(s, d) = \left\{OVPNC^1, OVPNC^2, \ldots, OVPNC^K\right\} \tag{6.33}$$

where, K is the possible number of OVPNCs for (s,d) pair; $OVPNC^k(s,d)$ is the k^{th} connection, that can be defined as a group of links.
The FWM light is detected at the receiver together with the desired signal light for an OVPNC and induced noise power, σ_{FWM}. It can be represented according to [85] as

$$\sigma_{FWM} = 2\rho^2 P_{ds} \frac{P_{pqr}(s,d)}{8} \tag{6.34}$$

where,

$$P_{ds} = P_i e^{-\alpha L} \tag{6.35}$$

In FWM case, the bit-error probability ,P_{be}^{FWM}, can be expressed as

$$P_{be}^{FWM} = 0.5erfc\left(SNR_{FWM}\right) \tag{6.36}$$

where, signal-to-noise ratio, SNR_{FWM}, for FWM crosstalk is,

$$SNR_{FWM} = \frac{I_{ds}}{\sigma_{FWM}\sqrt{2}} \tag{6.37}$$

6.2.3 Hybrid Crosstalk Model

The additional noise power, σ_{FWM}, generated due to FWM during the transmission of bit “1” also has impact on CQ. Assume that no power transmitted for “0” bit and can be neglected for analysis. Many of the researchers have considered either the impact of IB crosstalk or FWM crosstalk. Practically, both the crosstalk should be considered for the analysis of bit-error probability. Hence, we have mixed both IB and FWM crosstalk and called it as hybrid crosstalk model. The total noise power, σ_{hc}, due to hybrid crosstalk can be expressed as

$$\sigma_{hc} = \sqrt{\sigma_1^2 + \sigma_{FWM}^2} \tag{6.38}$$

Now the expression (6.22) can be modified based on hybrid crosstalk and at receiver the bit-error probability, p_{be}^{hc}, can be expressed as

$$\begin{aligned} p_{be}^{hc} = \tfrac{1}{4}erfc\left(\frac{I_{th}}{\sqrt{2\sigma_0^2}}\right) + \tfrac{1}{8}erfc\left(\frac{y}{\sqrt{2\sigma_0^2}}\right) \\ + \tfrac{1}{2^{N+3}}\left\{\prod_{k=1}^{N} f\left(y\right)\right\} \sum_{k=1}^{N} erfc\left\{\frac{B_k}{\sqrt{2\sigma_{hc}^2}}\right\} \end{aligned} \tag{6.39}$$

where, σ_{hc}^2 is the noise variance due to hybrid crosstalk; $B_k = y - \sum_{k=1}^{N} A_k$ and $y = I_{ds} - I_{th}$. It is known that higher the BER means lower the Q-Factor and vice versa. Hence, the

Q-Factor due to the impact of hybrid crosstalk can be mathematically written as

$$Q - Factor_{hc} = \frac{1}{p_{be}^{hc}} \tag{6.40}$$

6.3 Hybrid Crosstalk and WA Dependent OVPNC Selection Mechanism

Crosstalk occupies the same band as the desired signal and therefore it cannot be filtered out. Hence, it is the main cause of signal degradation in all optical networks. It is possible to minimize the impact of crosstalk by selecting appropriate connection among certain possible OVPNCs for a connection request in a WDM/DWDM network. In order to solve this problem, we proposed a hybrid crosstalk and WA dependent OVPNC selection mechanism. It can be evaluated based on OVPNCM mentioned in Figure 6.2.

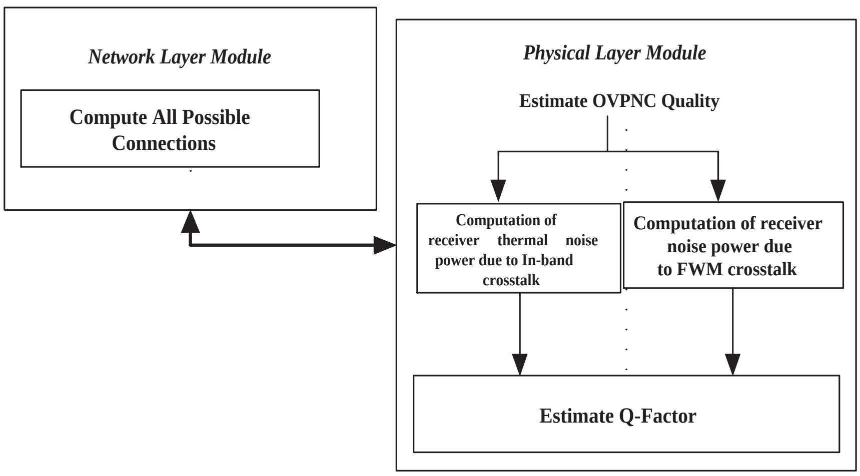


Figure 6.2: Hybrid Crosstalk Based OVPN Control Manager.

The network layer module helps to compute the possible connections. However, the physical layer module helps to compute the individual CQ depending on noise power due to IB and FWM crosstalk. Based on the impact of hybrid crosstalk, Q-Factor of individual connections are dynamically estimated using Equation (6.40). If the estimated Q-Factor value of any connection is greater than or equal to the threshold value of Q-Factor (Q_{th}), then that connection is assumed to be of good quality connection and can be provided to the OVPN client depending on the availability of the wavelength. As mentioned in literature, the Q_{th} value is assumed to be 10^9 i.e., $1/BER$, where BER is 10^{-9}. Before the final selection of OVPNC, an wavelength will be assigned using a WA scheme. The acceptance or rejection of a connection also depends on the efficiency of the WA schemes.

Figure 6.3 and 6.4 represent the flowchart for this mechanism. In order to achieve better CQ, a WA scheme is proposed in next section.

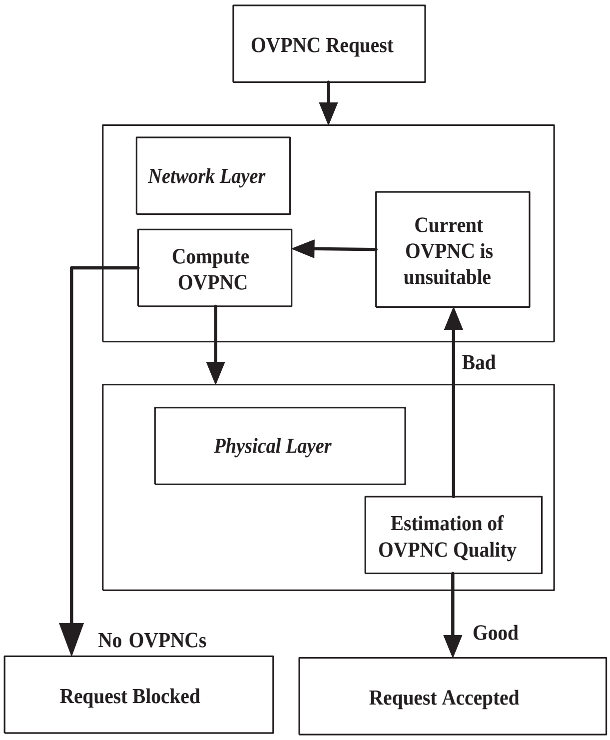


Figure 6.3: Block Diagram of Hybrid Crosstalk Based OVPNC Selection Mechanism

6.4 Proposed Inner-Outer Band (PIOB) WA Scheme

WA scheme is very important in order to reduce the connection blocking probability of the network. It can follow either wavelength continuity or wavelength conversion capability of the WDM network. Mostly, two types of WA schemes such as first-fit and random method are used in optical network with some modifications. An existing WA scheme is proposed [55,56] for wavelength routed optical networks in the presence of FWM crosstalk. It is also known as existing middle-outer band with random WA (EMOBRWA).

When a light propagates through several concatenated fiber links, it may encounter different co-propagating lightpaths and may experiences different FWM crosstalk components. Hence, the FWM induced crosstalk depends upon the dynamic state of the network [55]. The inherent nature of FWM induced crosstalk affects significantly the wavelengths present at the center of the transmission window, rather than the wavelengths present on the either side of the window. In order to avoid this effect, WDM

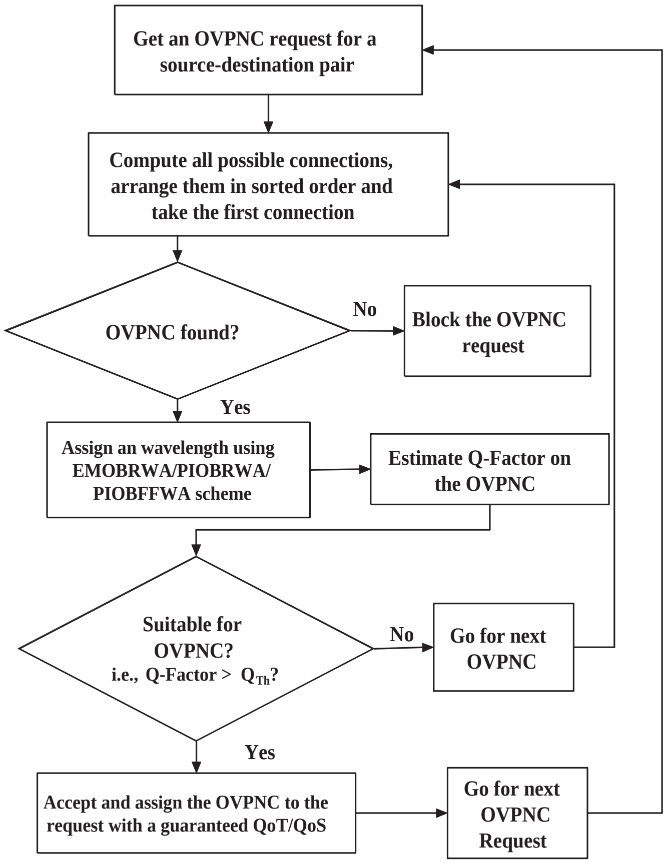


Figure 6.4: Flowchart of Hybrid Crosstalk Based OVPNC Selection Mechanism

channels can be designed with unequal wavelength spacing. No doubt this method produces FWM components at different wavelengths that does not interfere with the existing signal wavelengths. However, the major problem is that the transmission window broadens to accommodate all channel. In a fiber, we have other sources of impairments like switch crosstalk, ASE, shot noise and thermal noise other than FWM noise. Under certain situations, the contribution from other noise sources may dominate the FWM induced noise. Hence, unequal channel spacing is not a good option, where transmission bandwidth is sacrificed.

The EMOBRWA scheme assumes equal channel spacing and divides the entire wavelength ranges of an optical link into three parts such as one middle band and two outer bands. The wavelengths from these bands are assigned randomly to a connection.

By taking reference of EMOBRWA, we have designed a new WA scheme called as PIOB WA. It divides the entire wavelength ranges (transmission window) into four bands as shown in Figure 6.5 such as outer band (OB), complimentary outer band (COB), inner band (IB) and complimentary inner band (CIB). The OB and COB are reserved for the longer distance OVPNC. However, IB and CIB are reserved for the smaller distance OVPNC.

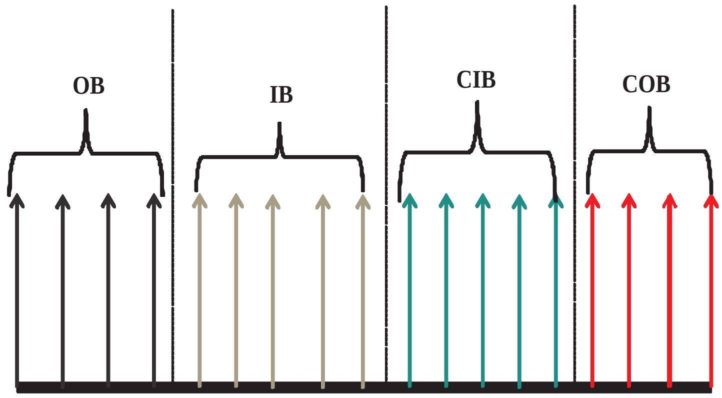


Figure 6.5: Transmission Window in PIOB WA Scheme.

The WA is done depending on the distance (d) covered by an OVPNC and the threshold distance (d_{thrs}). It is defined as the average distance covered by the existing OVPNCs in the network. The flowchart for the PIOB WA Scheme is presented in Figure 6.6. Further the WA in individual bands are done by using either first-fit (PIOBFFWA) or by random assignment (PIOBRWA) method.

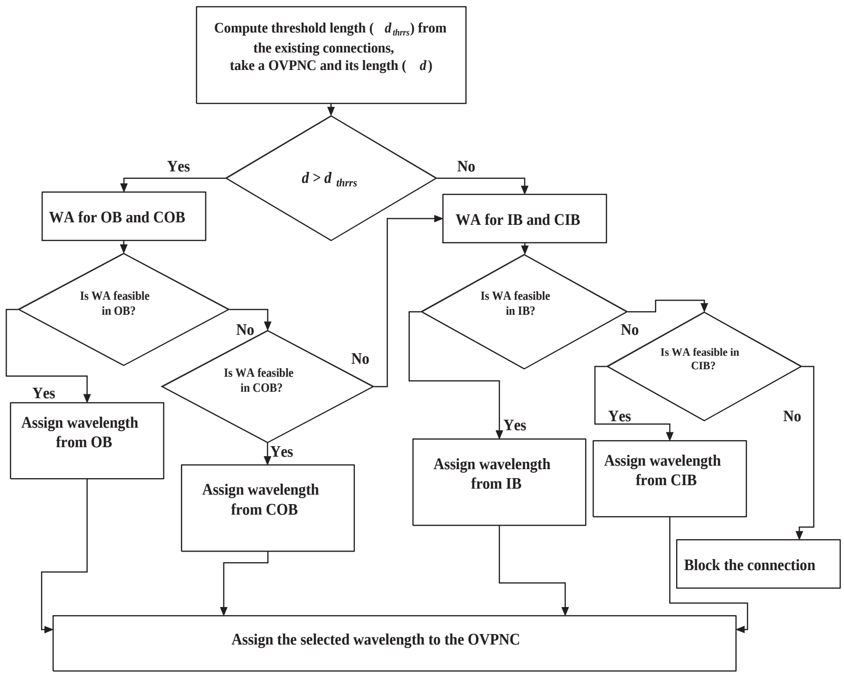


Figure 6.6: Flowchart of PIOB WA Scheme, Threshold Distance: d_{thrs}, Length of an OVPNC: d.

6.5 Simulation and Results

Following assumptions have been made for simulation.

- All the nodes presented in the topology are of same type.
- All PER and OCR have same functionalities.
- All Links have same number of wavelengths for transmission.
- The effect of shot noise, thermal noise have been neglected.
- It is assumed that all the interfering signals have same amount of IB crosstalk level.
- Wavelength continuity constraint is maintained for all OVPNCs.
- It is assumed that there is no existing OVPNC for any source-destination pairs.

Parameters considered for simulation are shown in Table 6.2. The proposed algorithm is demonstrated by using NSFNet topology of 10 nodes and 16 links shown in Figure 3.7.

Table 6.2: Parameters used in simulation

Parameters	Values
Receiver's responsivity, ρ	1
Thermal noise, σ_0	0.05mA
Signal current, I_s	1mA
Detection threshold, I_{th}	$\frac{1}{2}(I_s)$
Input powers, P_p, P_q, P_r	3mW
Fiber attenuation, α	0.2dB/km
Degeneracy factor, d	3 if $f_i = f_j$ and 6 if $f_i \neq f_j$
Efficiency, η	0 to 1
Effective area, A_{eff}	$5 \times 10^{-7} cm^2$
Chromatic dispersion, D_c	0.3 ps/nm-km
Dispersion slope, $dD_c/d\lambda$	$0.07 ps/nm^2$
Central wavelength, λ_k	$1.55\mu m$
Crosstalk level, ϵ_k	-25dB
Nonlinear coefficient, γ	$2.35(\text{w.km})^{-1}$

The following sub-sections discuss the simulation results.

6.5.1 Analysis of Q-Factor with IB Crosstalk Components

The simulation result explains about the performance degradation of link quality due to IB crosstalk components (interfering channels). In Figure 6.7, the Q-Factor per link is plotted as a function of input power with different number of IB crosstalk components (N). This figure demonstrates about the impact of IB crosstalk components on the computation of link Q-Factor. It shows that Q-Factor values decrease as the number of crosstalk component increases. This is the reason of considering the IB crosstalk component as a key parameter, which has impacts on OVPNC quality.

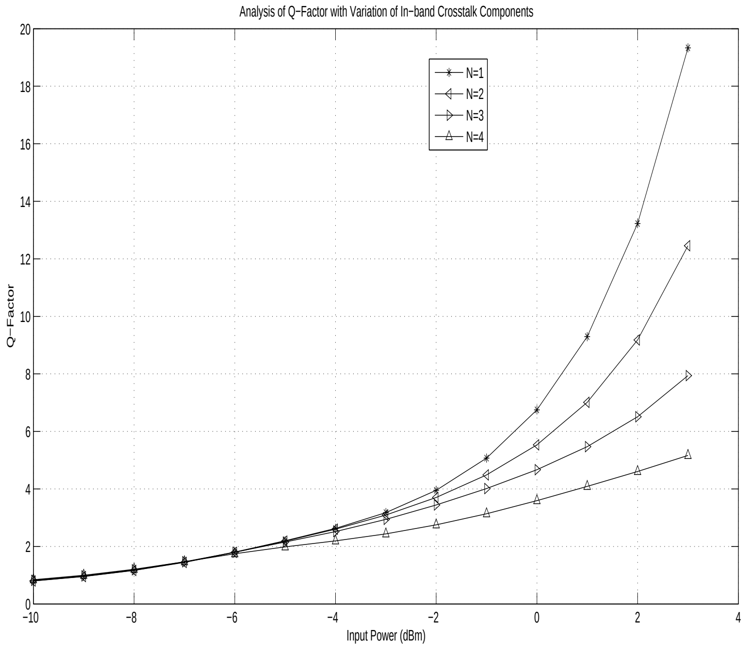


Figure 6.7: Q-Factor vs. Input power at Different Number of IB Crosstalk Components

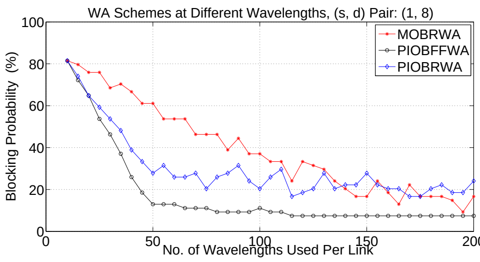
In order to analyse the Q-Factor of a connection based on the hybrid crosstalk, we have applied our proposed as well as one of the existing WA scheme for comparison purposes.

6.5.2 OVPNC Blocking Probability with the Variation of Wavelengths

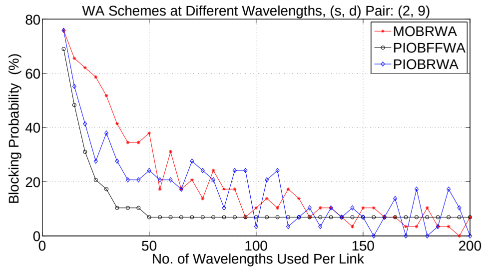
The second analysis is variation of wavelengths per link and its impact on connection blocking probability. It can also be described as the number of connections blocked out of computed number of possible connections for a source-destination pair with respect to the availability of wavelengths. The plots shown in Figure 6.8(a), 6.8(b) and 6.8(c) say that PIOB WA schemes are performed better than the existing middle-outer band with random WA (MOBRWA). In case of PIOBFFWA, the OVPNC blocking probability is almost constant at higher wavelength range.

6.5.3 Computation of Guaranteed OVPNCs

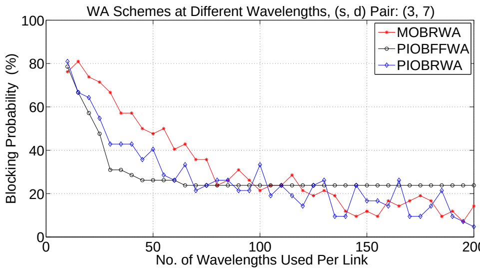
The third case analyses the performances of WA schemes by computing the number of guaranteed OVPNCs (GOVPNCs) for a source-destination pair. The Q-Factor values of all the guaranteed OVPNCs are above the threshold i.e., 10^9. Let us take a source-



(a) Source: 1, Destination: 8.



(b) Source: 2, Destination: 9.



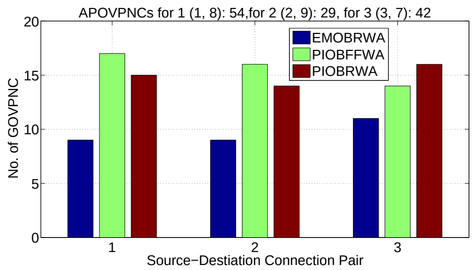
(c) Source: 3, Destination: 7.

Figure 6.8: OVPNC Blocking Probability vs. No. of Wavelengths per link.

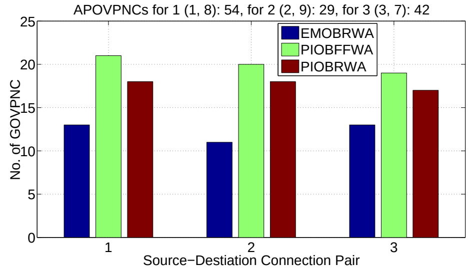
destination pair (3,7) in Figure 6.9(a), whose number of possible OVPNCs are 42. Out of 42 connections, the Q-Factor of 14 OVPNCs for PIOBFFWA are above 10^9 called guaranteed OVPNC and the remaining are unsuitable for connection setup. The number of guaranteed OVPNC for the case of PIOBRWA and EMOBRWA are 16 and 11 respectively. Similarly, the number of possible and guaranteed OVPNCs are presented in Figure 6.9(b), 6.9(c) and 6.9(d) at different wavelengths. These plots clearly say that the PIOB WA schemes are always performed better than the EMOBRWA scheme. These plots also project that, with higher number of wavelengths for a link, the number of guaranteed OVPNCs will be more. It is because of more number of available wavelengths in a link.

6.5.4 Blocking Probability with the Variation of Number of OVPNC Request

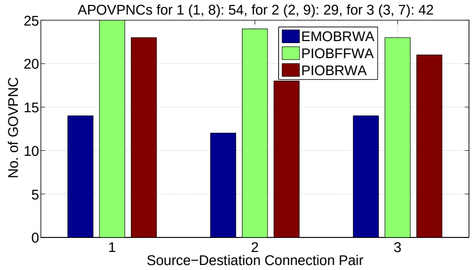
The fourth case analyses the performance of hybrid crosstalk based OVPNC selection mechanism for different WA schemes. Figures 6.10(a), 6.10(b), 6.10(c) and 6.10(d) present the performances in terms of blocking probability against the number of OVPNCs request for a source and destination pair. An uniform traffic pattern is considered in the form of OVPN connection requests.The simulation plots are taken at different number of wavelengths. The number of wavelengths used in Figures 6.10(a), 6.10(b), 6.10(c) and 6.10(d) are 15, 20, 25 and 35 respectively. The result demonstrates that the OVPNC selection



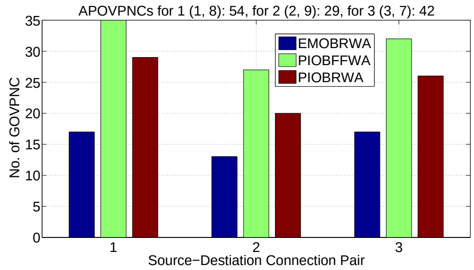
(a) No. of Wavelengths: 15.



(b) No. of Wavelengths: 20.

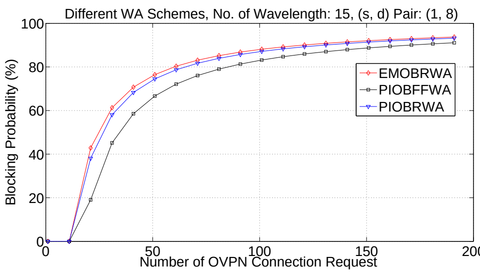


(c) No. of Wavelengths: 25.

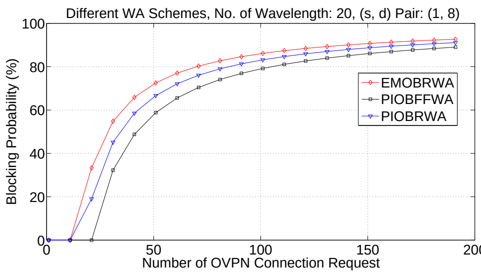


(d) No. of Wavelengths: 35.

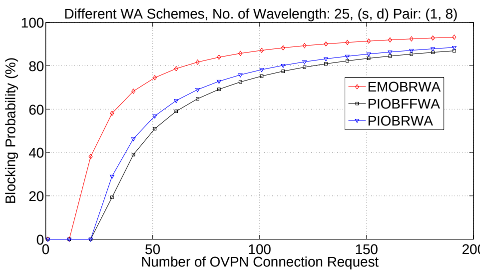
Figure 6.9: Guaranteed OVPNCs vs. Source-destination Connection Pair, Source-Destination Pairs: (1,8), (2,9), (3,7).



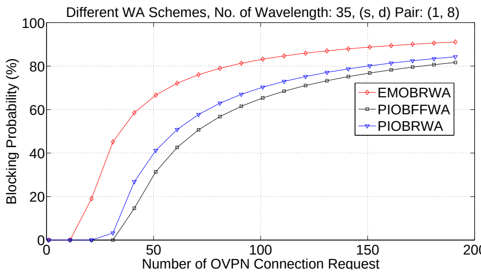
(a) No. of Wavelength: 15.



(b) No. of Wavelength: 20.



(c) No. of Wavelength: 25.



(d) No. of Wavelength: 35.

Figure 6.10: Blocking Probability vs. No. of OVPNC Requests (Source: 1, Destination: 8.)

mechanism with PIOB WA scheme has the least blocking probability. The plots also say that the blocking probability decreases slowly with the increase of wavelengths.

6.6 Conclusion

This chapter demonstrates the impact of linear and non-linear PLIs on transparent optical networks. It mainly focuses on hybrid (linear and non-linear) crosstalk i.e., mixing of IB and FWM and tries to incorporate it's impact on RWA algorithm. BER due to hybrid crosstalk in a WDM receiver has been studied and computed results have been expressed in terms of Q-Factor. A new WA scheme called PIOB WA is proposed for the efficient selection of OVPNC with guaranteed QoT/QoS. The proposed hybrid crosstalk model with PIOB WA scheme is very useful for high speed WDM/DWDM networks, where the impact of PLIs are very high. This thesis has demonstrated the proposed mechanism and presented the OVPN performance in terms of blocking probability. The simulation results say that the OVPNC selection mechanism based on hybrid crosstalk with PIOB WA scheme reduces the connection blocking probability by utilizing the available network resources. It provides guaranteed quality of transmission as compared with one of the existing scheme called as EMOBRWA. The proposed mechanism is not only Q-Factor friendly, but also wavelength efficient one.

CHAPTER 7

Conclusions, Limitations and Future Works

Preface

In this chapter, we summarize the contributions detailed in Chapter 3 to Chapter 6. Some important conclusions are also drawn and important limitations are discussed. Finally, scope for future developments and possible extensions of the present work are discussed.

7.1 Concluding Remarks

As WDM/DWDM networks carry huge volume of OVPN traffic, maintaining a high level of OVPN service with guaranteed QoS is an important issue. It is essential to analyse and maintain the CQ as per the QoS requirements. The types of application being deployed across the public Internet today are increasingly mission-critical, owing to which business success can be jeopardized by poor quality of the network. It does not matter how attractive and potentially lucrative the applications are if the network does not provide the guaranteed quality consistently. The choices for the selection of suitable OVPNC with required quality can be provided by the service provider network to the client.

This thesis addresses the QoS estimation techniques for the selection of OVPNC with required and highest Q-Factor under dynamic OVPN traffic demand. We have developed four different QoS estimation techniques and used it for the section of OVPNC along with wavelength assignments. The proposed techniques have been evaluated with different scenarios based on client QoS requirements and network traffic (loads). As per the OVPN client need, the required Q-Factor should satisfy the computed Q-Factor of an OVPNC, which is a combination of network and physical layer QoS constraints. It will be good if multiple QoS constraints are combined together in one unit to represent the characteristic of an OVPNC. Hence, this research work has proposed four different QoS estimation techniques to represent the combined units as a Q-Factor. A connection can be characterized with multiple QoS constraints such as data rate, delay and BER etc. If the connection is selected based on a single QoS constraint such as data rate, then the quality of a selected OVPNC for a client might not be satisfied with other requirements such as delay and BER. However, if the OVPNC is selected based on Q-Factor, then the connection is expected to be well suited to the client's quality requirements. The system performs global computation by the use of centralized OVPNCM based on wavelength assignment, required and computed Q-Factor. The outcome of the global computation will be a new decision criteria for the selection of quality based OVPNC along with wavelength assignment. In the following section, we have detailed the contributions made in this thesis to address the OVPNC selection with QoS requirements.

7.2 Contributions

The contributions from this thesis can be listed as follows.

- Fiber material based estimation of OVPN connection quality.

  This work demonstrates the QoS analysis mechanism of a connection by taking different type of fiber materials and range of wavelengths for all possible OVPNCs. An algorithm for the computation of all possible OVPNCs is proposed. Using this technique, service provider network can use OVPNCM and decide the type of fiber to be deployed as per the QoS requirement of the client. It demonstrates that how the fiber material with silicon oxide composition provides highest quality to the client. It also presents the improvement of connection acceptance with increase in number of wavelengths per connection.

- Total dispersion based estimation of OVPN connection quality.

  It deals with dispersion effects in an optical link. Due to various dispersion effects in a fiber link, the connection quality degrades substantially. It can be analysed by the service provider network and accordingly proper action can be taken to avoid the degraded connection quality. This also demonstrates OVPNC/wavelength assignment mechanism for different OVPN types such as all possible, shortest and disjoint OVPN. In simulation, it is shown that all possible OVPN type performs better than others.

- Noise and eye penalty based estimation of OVPNC quality.

  Using this technique, service provider network can analyse the connection quality based on the mixing effect of LIs. The simulation result demonstrates the performance of all OVPN types with assignment of highest Q-Factor as well as required Q-Factor at different wavelengths.

- Hybrid impairment based estimation of OVPN connection quality.

  This technique is helpful to analyse the connection quality based on the mixing effect of linear IB and non-linear FWM crosstalk along with wavelength assignment. This proposes a new WA technique and compares it with few existing WA techniques. The proposed WA technique is useful in improvement of OVPNC quality.

7.3 Limitations of the Work

Following are some of the limitations of our work.

- The proposed work presents a generalized analysis of connection quality without considering any application area.
- The path restoration techniques have not been considered during link failure.
- The comparative study of centralized and distributed system has not been undertaken.
- Optimization technique for the selection of OVPNC based on various QoS constraints has not been used.
- The practical implementation of the proposed work have not been done.
- The simulation works carried out in this thesis have been done using MATLAB. More accurate results can be obtained by using commercial software like Optiwave and Optisim.
- This thesis considered uniform traffic pattern in all cases. It is expected that similar result will apply when the traffic pattern changes.

7.4 Future Directions

Based on the above limitations of the work and the work reported here, following are some of the possible directions for future research.

- The proposed research work deals with the computation of Q-Factor for the selection of OVPNC using various QoS estimation techniques and it is proposed that these techniques can be applied for storage area network. It can be used for high quality data transfer as well.
- It is proposed to apply these QoS estimation techniques with wavelength conversion capabilities of all the routers.
- It is proposed to design an algorithm for path restoration during the time of OVPN link failure.
- A comparative study can be taken up for centralized and distributed OVPN network.

- It is proposed to design an optimization technique to deal with all the proposed QoS analysis techniques.
- It is proposed to develop an optical network simulator for the analysis of QoS.
- Performance of the networks for variable traffic pattern can be considered to provide comparative results to the proposed works.

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Publications from the Thesis

Journals

1. **S. K. Das**, P. Kalyan and S. K. Patra, "Data-path Selection mechanism based on Physical Layer Impairments for WDM Network," *International Journal of Signal and Imaging Systems Engineering (IJSISE)*, vol. 5, no. 4, pp. 239-245, 2012.

2. **S. K. Das**, V. V. Dhanya and S. K. Patra, "QoS Based OVPN Connection Setup and Performance Analysis," *WSEAS TRANSACTIONS on COMMUNICATIONS*, E-ISSN: 2224-2864, vol. 11, no. 8, pp. 275-286, 2012.

3. **S. K. Das** and S. K. Patra, "QoS Aware Optical Virtual Private Network (OVPN) Analytical Control Plane Mechanism," *International Journal of Computer and Electrical Engineering*, ISSN: 1793-8163, vol. 4, no. 2, pp. 336-340, 2012.

4. **S. K. Das** and S. K. Patra, "Physical Layer Impairments Aware OVPN Connection Selection Mechanism," *International Journal of Computer and Electrical Engineering*, ISSN: 1793-8163, vol. 4, no. 2, pp. 331-335, 2012.

5. **S. K. Das** and S. K. Patra, "Optical Power Aware Quality Analysis for the Selection of Optimal OVPN Connection over WDM Network," *IETE Technical Review*, vol. 29, no. 6, pp. 492-498, 2012.

6. **S. K. Das** and S. K. Patra, "Hybrid Crosstalk Aware Q-Factor Analysis for Selection of Optical Virtual Private Network Connection," *Taylor & Francis International Journal of Electronics*, 2013 (Accepted).

Conference Proceedings

1. **S. K. Das**, S. K. Naik and S. K. Patra, "Fiber Material Dependent QoS Analysis and OVPN Connection Setup over WDM/DWDM Network," in *IEEE TENCON*, pp. 521-525, November, 2011.

2. **S. K. Das**, S. K. Naik and S. K. Patra, "Centralized Data-path Control Mechanism for DWDM/GMPLS Network," in *International Conference on Signal Acquisition and Processing (ICSAP)*, Singapore, February, 2011.

3. **S. K. Das**, T. R. Swain and S. K. Patra, "Impact of Crosstalk & Crosstalk Aware Data Path Selection in Optical WDM/DWDM networks," in *IEEE International Conference on Advances in Engineering, Science and Management (ICASEM)*, India, pp. 180-185, March, 2012.

4. **V. V. Dhanya**, S. K. Das and S. K. Patra, "QoS Based Light-path Provisioning and Performance Analysis in WDM Network," in *IEEE International Conference on Computing, Electronics and Electrical Technologies (ICCEET)*, India, pp. 659-662, March, 2012.

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  Council of Higher Secondary Education, Odisha, India [First class]
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Professional Experience

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- Software Engineer (Firmware), Actatek, Singapore January 2008 – July 2009
- Network Engineer (Software), Netmarks, September 2007 – November 2007
- Research Associate (R & D), CEMNet Lab, NTU, Singapore, March 2007 – September 2007
- Software Integration Engineer, Motorola Electronics Pvt. Ltd, Singapore, December 2006 – February 2007
- Research Engineer, A-STAR, Singapore, July 2002 – December 2006
- Lecture, VSSUT, Burla, Odisha, India, July 1998 – July 1999

Publications

- 05 Journal Articles
- 14 Conference Articles
- 04 Prototype Invention (Patent)